Rare-Earth Mineral Deposits of the Mountain Pass District San Bernardino County California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 261

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By J. C. OLSON, D. R. SHAWE, L. C. PRAY, *and* W. N. SHARP

With a foreword on

History of the Discovery at Mountain Pass, California

By D. F. HEWETT

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A geologic study of the district and its rare-earth-bearing carbonate rocks. One deposit, the Sulphide Queen carbonate body, is the greatest concentration of rare-earth minerals now known. Some data are given on radioactive minerals, principally thorite and monazite

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FOREWORD

HISTORY OF DISCOVERY AT MOUNTAIN PASS, CALIFORNIA

By D. F. Hewett

The region near Mountain Pass, San Bernardino County, Calif., has been the scene of at least three cycles of prospecting for minerals; the discovery of deposits containing large amounts of rare-earth minerals in April 1949 marked the beginning of the third cycle.

The first cycle began about 1861 when a horde of prospectors swarmed over southern Nevada and southeastern California, following the decline in discovery and production of gold along the western slope the Sierra Nevada. In 1854 lead ore was found in the Yellow Pine district (Potosi area) on the west slope of the Spring Mountains in southern Nevada. In the early sixties, prospectors began to explore southward into California and in 1865 enough discoveries had been made near Clark Mountain [fig. 1] to warrant the organization of a mining district, Clark district. Soon thereafter, the New York and Providence districts were organized in the New York and Providence Mountains. By 1870 many silver-bearing veins had been discovered and explored on the north slope of Clark Mountain, 10 miles north of Mountain Pass. During the next 25 years, these mines yielded about $5,000,000 worth of silver. It is reported that during the height of activity, the population of the Clark district was about 500; in 1895, only 50 persons remained. All that now remains of the principal town, old Ivanpah, about 8 miles north of Mountain Pass, are the walls of several adobe houses.

In this first cycle, copper deposits were found and explored at and near the Copper World mine, 5 miles west of Mountain Pass; lead deposits were worked at the Mohawk mine, 4 miles west; and gold and copper deposits on Mineral Hill, 4 miles southeast of Mountain Pass. In all of these areas activity declined during the early nineties. There was a slight revival after a branch of the Santa Fe Railroad was built from Goffs to Barnwell in 1892, to permit exploration of the gold veins at Vanderbilt, near Barnwell, which lies about 20 miles southeast of Mountain Pass. Theretofore, all supplies needed for mining were brought by wagons from San Bernardino, about 200 miles west.

The second cycle of prospecting in the Clark district began in the late nineties and was stimulated by the completion of the Union Pacific Railroad (Los Angeles and Salt Lake Railroad) in 1905. A real mining boom began during the war years of 1917–18, and under the influence of the high prices obtained for copper, lead, and zinc, prospecting and production reached a new peak and many mines were then active that have been idle ever since. Mining activity declined after the war but the higher price offered for lead during 1924 again stimulated search for lead deposits. In September 1924, Fred B. Piehl of Goodsprings, Nev., and associates prospected for lead deposits on Sulphide Queen Hill, sank several pits and shallow shafts, and located four claims. Small amounts of galena are present on the dumps but no ore was ever shipped.

In October 1924, D. F. Hewett of the U. S. Geological Survey, having finished the study of the Goodsprings district, Nevada, began the study and mapping of the Ivanpah quadrangle, an area of about 3,900 square miles near the center of which the Mountain Pass district lies. Field work in the part of the quadrangle near Mountain Pass was begun in October 1926 and continued through the winter. The large area of pre-Cambrian crystalline rocks that extends north and southeast of Mountain Pass was mapped and studied; within a square mile south of present U. S. Highway 91, three large bodies of syenite, an unfoliated intrusive rock, were mapped. The large body of shonkinite and syenite which lies a mile north of the highway and in which the Birthday veins are now known, was not found in 1926. In the fall of 1926, the only active mine near Mountain Pass was Wade's antimony mine, about 2 miles north of the Birthday shaft.

In 1933 the rise in the price of gold induced prospectors to search for gold-bearing veins, and in December Fred B. Piehl returned to the Sulphide Queen Hill and, finding a good assay for gold in rock from a shallow shaft northeast of the hill, located 3 more claims adjoining the 4 previously located for lead. This shaft later became the Sulphide Queen shaft. Most of the work at the mine, including development of the shaft (now 365 feet deep) and numerous levels, was done by J. C. Howard during 1939–41 under an option to purchase from the owners, Piehl and his associates. In 1941–42, about $12,000 worth of gold was produced but no work has been done since then.

The third cycle of prospecting and discovery may be said to have begun in late March 1949 when Marty Hess, an engineer, appeared in Goodsprings, Nev., to give a talk on the search for uranium. Hess's visit was sponsored and financed by Donald Cameron of the Nevada Department of Education. Among those present in the schoolhouse when Hess gave his talk was Herbert S. Woodward, an engineer employed locally. In reviewing the occurrence of uranium, Hess mentioned the common association of uranium and cobalt, an element that was known to occur widely in ores of the Goodsprings district. After the meeting, Woodward discussed with several of the local miners the idea of searching for uranium with a Geiger counter in those parts of the district known to contain cobalt minerals. P. A. Simon, owner of a service station and motor court at Jean, 8 miles southeast of Goodsprings, offered to buy a counter for an interest in the enterprise.

After two weeks spent in testing the dumps of many prospects and mines and finding nothing that was radioactive, Woodward became discouraged. He confided his discouragement to Fred B. Piehl, who suggested that, before giving up the search, Woodward examine and test specimens of minerals and rocks at his cabin, collected from a large area in southern Nevada and adjacent parts of California. To their surprise, specimens of lead and gold ores from the Sulphide Queen Hill were radioactive. Woodward and his wife quickly proceeded to the Sulphide Queen mine, a mile or two northeast of Mountain Pass, and soon found that much of the material on the Sulphide Queen mine dump and hill nearby was radioactive. Because the ground was held under the original lead and gold claims made by Piehl, Woodward searched the hills that lay a mile or more northwest. At this time, Clarence Watkins of Goodsprings joined Woodward and Simon as a third partner. On April 23, 1949, the partners found intense radioactivity along the outcrop of a vein, about 4,000 feet northwest of the Sulphide Queen shaft, and located the Birthday claim, named for its discovery on Woodward's birthday anniversary. A shallow pit showed the presence of about 6 feet of vein which contained a large amount of a light-brown heavy mineral. Not recognizing it and not having the facilities to determine its identity, they submitted a specimen of the heavy mineral to E. T. Schenk, at the Boulder City station of the U. S. Bureau of Mines. A spectroscopic test showed the presence of considerable rare-earth oxides, fluorine, and carbon dioxide and indicated that the mineral was bastnaesite.

Through May and June, other veins were found nearby and more claims were located. Through J. W. Wilson, a friend in Las Vegas, Nev., Hewett learned of the discovery on May 29 and asked the owners to send specimens, which they did in mid-June. As one result, Hewett visited the area on July 15 and with Woodward, Watkins, Simon, and Schenk, examined the existing openings: several shallow trenches and one 8-foot shaft on the original Birthday vein. The material in each of the pits was very radioactive and other areas nearby also showed noteworthy radioactivity. Even at that time, it seemed that considerable bastnaesite with some thorium-bearing minerals must be present in the local area.

Later in July the identity of the mineral, bastnaesite, was confirmed in Pasadena by Hewett and by mineralogists in the U. S. Geological Survey laboratory in Washington, D. C., and arrangements were made for a program of geologic study and mapping in the Birthday area by the Geological Survey. Geologic mapping of the Birthday area was begun on November 3, 1949, by W. N. Sharp of the Survey and Lloyd C. Pray, of the Geology Department, California Institute of Technology, Pasadena, who also was employed by the Geological Survey. By November 18, enough had been learned about the nature and extent of the veins and their associations to warrant a public announcement, and a statement by the Secretary of the Interior was released to the public on November 18. Soon thereafter, a similar announcement was made by the California Division of Mines.

There were at least two results of these announcements: representatives of several large mining companies soon sent engineers to examine the discoveries, and some of these made offers to purchase the Birthday group of claims; and many prospectors soon visited the areas nearby to search for similar veins. In February 1950, the Birthday group of claims were bought by the Molybdenum Corporation of America, and in May the company began to sink the Birthday shaft. Among the prospectors who visited the Mountain Pass area during February and March 1950 were Otto Krone of San Francisco, William Benson and George Watkins, Reynolds Robbins of Goodsprings and J. B. Kasey of Bakersfield, Calif. Many veins containing rare-earth minerals were found in the low hills west and south of the Birthday group and in the hills as much as 5 miles south of Highway 91, or 7 miles south of the Birthday. An inquiry indicates that each of the prospectors carried a Geiger counter and all of the veins found were radioactive.

The field work of Pray and Sharp in November and December 1949 showed that the veins on the Birthday claims fill fractures in a large body of an uncommon igneous rock, shonkinite, and that it was the earliest of four potash-rich rocks, shonkinite, syenite, granite, and later shonkinite which occurs as dikes both in the large shonkinite body and pre-Cambrian crystalline rocks nearby. As a result of this work by Pray and Sharp it seemed probable, as early as January 1950, that other veins carrying rare-earth minerals would probably be found throughout the belt within which bodies of syenite and shonkinite had been found in the mapping and study of the area during the fall of 1926. Because prospectors were finding veins containing rare earths as far southeast as Kokoweef Peak during February and March 1950, it seemed advisable to study and make a geologic map of the entire belt within which the uncommon igneous rocks were found.

On August 3, 1950, J. C. Olson of the Geological Survey arrived at Mountain Pass to plan the district study with D. F. Hewett. Aerial photographs on the scale of about 1,800 feet to the inch were used for the mapping by Olson. Through mid-August all field work was done south of the highway. On August 28–29, Hewett again visited Olson and they examined the area between the highway and the Birthday claims and found the large body of rock, largely made up of barite and several carbonates, that is referred to herein as the Sulphide Queen carbonate body. Examination of the entire area, 20 acres in extent, with a Geiger counter showed radioactivity as great as 2 to 5 times the background count. The persistent high barite content indicated that the body might be a commercial source of that mineral, and 15 large specimens were collected for specific gravity determinations. These indicated that the average barite content was about 20 percent. Soon thereafter, plans were made to make systematic tests over the entire area of the barite-carbonate rock, and this was undertaken by W. N. Sharp when he joined Olson in October.

Meanwhile, because the persistent radioactivity indicated small amounts of a thorium-bearing mineral and the mineralogy of the deposit resembled that of the Birthday veins, it was decided to examine thin sections of the first 15 specimens for the presence of bastnaesite. Two thin sections contained about 10 percent of bastnaesite and more than average amounts of barite. About mid-October a second group of about 15 specimens was selected from those parts of the barite-carbonate body which contained more barite than the average; all of these specimens contained noteworthy bastnaesite. One of these from a prominent outcrop at the southwest end of the barite-carbonate body contained about 30 percent bastnaesite, but this material was only slightly radioactive. By early November, it had been determined that this outcrop is largely made up of bastnaesite and barite and that the average rare-earth content for the outcrop, which is about 100 by 120 feet, is about 20 percent. Also, it was determined that a large part of the entire body of barite-carbonate rock contains from 5 to 15 percent bastnaesite.

It is probable that Otto Krone of San Francisco was among the first of the new group of prospectors to explore the area near Mountain Pass for radioactive minerals. Krone went into the area in late January 1950 and about February 15, using a Geiger counter, he located the Onessa claim, south of Mountain Pass. In early March, having learned from Piehl the location of his group of claims on Sulphide Queen Hill, Krone located claims along the southwest border of the hill. On March 10, Krone brought to Hewett in Pasadena, several pieces of rock and asked to have them tested for bastnaesite. The thin sections cut from one piece showed about 30 percent of the mineral. Krone refused to reveal the source, beyond stating that they were obtained from the area north of the highway, but in 1952 he stated that this piece of rock came from the outcrop of high-grade rock at the southwest end of Sulphide Queen Hill. J. B. Kasey, of Bakersfield, probably went into the area in early March and located claims west of Sulphide Queen Hill. Reynolds Robbins of Goodsprings later discovered veins both north and south of the highway. William Benson and George Watkins located the Windy group and other claims northeast of Kokoweef Peak in March 1950. It has been reported that Kasey was able to enlist the interest of an eastern chemical manufacturing firm and that they sent an engineer to examine claims along the west slope of Sulphide Queen Hill in May 1950, but this was not known to Survey geologists until late August.

By late November 1950, the presence of bastnaesite in many parts of barite-carbonate body on Sulphide Queen Hill had been proven by microscopic work by the U. S. Geological Survey party, and it seemed advisable to verify the results by chemical analyses. These analyses, made by the Smith-Emery Company of Los Angeles, confirmed the results of the microscopic work and it was decided to issue a press release setting forth the results of the field work from early August to late December 1950. The release appeared in the press January 16, 1951. On January 18, the Piehl-Martin group of claims that covered Sulphide Queen Hill, was purchased by the Molybdenum Corporation of America. During the next 3 months, the company drilled several hundred vertical holes to an average depth of 50 feet and made many analyses of the cuttings for rare earths. The general results of this work were announced to the stockholders during October 1951, and they were described in an article in January 1952 by staff writers of the Engineering and Mining Journal.

Because of the need for more detailed mineralogical information, W. T. Pecora entered the program in July 1951 to coordinate field work with expanded laboratory investigations of mineralogy. In August, H. W. Jaffe collected specimens and began a systematic mineralogical study of the district; early in October, D. R. Shawe and J. C. Olson undertook additional detailed mapping of the Sulphide Queen carbonate body and vicinity, and this work was continued by Shawe in November and December.

The discovery and delineation of large and extraordinary mineral deposits are rarely the result of work by one or a few men. Commonly, the first discovery is made by one or several prospectors who, using well-known techniques, recognize a few minerals or metals in greater than average concentration. After a little exploration within the limits of their resources most of them either sell out or take in a new partner who adds his resources and knowledge. Commonly, again, after further work, the group then sells out to a company equipped with resources and special knowledge. Geologists rarely make the first discovery but generally they add special knowledge that clarifies some geologic relationships and controls.

At Mountain Pass two waves of prospectors recognized the lead and gold deposits but none found the veins of heavy rare-earth minerals within the area of known mineralization; during these cycles, portable instruments for measuring radiation had not been devised. The first prospectors of the third cycle, Woodward and Watkins, came equipped to search for radioactive minerals. They deserve great credit for the tenacity that led them to carry on the search after some discouragements. Curiously, even though it was the small amounts of thorium that led them to the veins, that element is not an essential constituent of the rare-earth mineral, bastnaesite.

It seems quite clear that several persons recognized the radioactivity and rare-earth content of parts of the barite-carbonate body in Sulphide Queen Hill before geologists examined it in August 1950. It seems clear, however, that the geologists, using well-known techniques such as polished and thin sections viewed under the microscope, definitely outlined the area within which rare-earth minerals occur on Sulphide Queen Hill and first recognized the body of high-grade barite-bastnaesite rock on the southwest end of that hill.

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RARE-EARTH MINERAL DEPOSITS OF THE MOUNTAIN PASS DISTRICT, SAN BERNARDINO COUNTY, CALIFORNIA

By J. C. Olson, D. R. Shawe, L. C. Pray, and W. N. Sharp

ABSTRACT

Bastnaesite, a rare-earth fluocarbonate, was found in the Mountain Pass district in April 1949. Subsequent geologic mapping has shown that rare-earth mineral deposits occur in a belt about 6 miles long and 1½ miles wide. One of the deposits, the Sulphide Queen carbonate body, is the greatest concentration of rare-earth minerals now known in the world.

The Mountain Pass district is in a block of metamorphic rocks of pre-Cambrian age bounded on the east and south by the alluvium of Ivanpah Valley. This block is separated on the west from sedimentary and volcanic rocks of Paleozoic and Mesozoic age by the Clark Mountain normal fault; the northern boundary of the district is a conspicuous transverse fault. The pre-Cambrian metamorphic complex comprises a great variety of lithologic types including garnetiferous mica gneisses and schists; biotite-garnet-sillimanite gneiss; hornblende gneiss, schist, and amphibolite; biotite gneiss and schist; granitic gneisses and migmatites; granitic pegmatites; and minor amounts of foliated mafic rocks.

The rare-earth-bearing carbonate rocks are spatially and genetically related to potash-rich igneous rocks of probable pre-Cambrian age that cut the metamorphic complex. The larger potash-rich intrusive masses, 300 or more feet wide, comprise 1 granite, 2 syenite, and 4 composite shonkinite-syenite bodies. One of the shonkinite-syenite stocks is 6,300 feet long. Several hundred relatively thin dikes of these potash-rich rocks range in composition from biotite shonkinite through syenite to granite. Although a few thin fine-grained shonkinite dikes cut the granite, the mafic intrusive bodies are generally the oldest, and granitic rocks the youngest. The potash-rich rocks are intruded by east-trending andesitic dikes and displaced by faults.

Veins of carbonate rock are most abundant in and near the southwest side of the largest shonkinite-syenite body. Most veins are less than 6 feet thick. One mass of carbonate rock near the Sulphide Queen mine is 700 feet in maximum width and 2,400 feet long. About 200 veins have been mapped in the district; their aggregate surface area is probably less than one-tenth that of the large carbonate mass.

The carbonate minerals, which make up about 60 percent of the veins and the large carbonate body, are chiefly calcite, dolomite, ankerite, and siderite. The other constituents are barite, bastnaesite, parisite, quartz, and variable small quantities of crocidolite, biotite, phlogopite, chlorite, muscovite, apatite, hematite, goethite, fluorite, monazite, galena, allanite, cerite, sphene, pyrite, chalcopyrite, tetrahedrite, malachite, azurite, strontianite, cerussite, wulfenite, aragonite, and thorite. The rare-earth oxide content of much of the carbonate rock is 5 to 15 percent; in some local concentrations of bastnaesite the rare-earth oxide content is as high as 40 percent.

The foliation and inclusions in the Sulphide Queen carbonate body, and the discordant contacts between this body and the gneissic wall rocks, show that the carbonate rock was intruded as a mass into its present position. Radioactive age determinations on monazite from the Sulphide Queen carbonate body indicate a tentative age of about 900 to 1,000 million years (pre-Cambrian), and the potash-rich rocks are at least as old and thus are of pre-Cambrian age. Four tentative determinations of 800 to 900 million years for the age of zircon in shonkinite at the Birthday shaft also indicate the pre-Cambrian age of the potash-rich rocks.

The relation of the carbonate rocks to alkalic igneous rocks is similar to rock associations found in certain other parts of the world. Because of structural reasons, as well as the pre-Cambrian age of the monazite, the rare-earth-bearing carbonate rock could not have originated as sedimentary limestone or dolomite of Paleozoic age or through assimilation of sedimentary rocks of Paleozoic age by the parent magma of the potash-rich rocks. The carbonate rock might have had a sedimentary origin in the pre-Cambrian gneissic complex as limestone or evaporite, subsequently modified and squeezed into discordance with the foliation of the metamorphic rocks. A magmatic origin of the rare-earth-bearing carbonate rock by differentiation of an alkaline magma from shonkinite to syenite to granite, with a carbonate-rich end-product containing the rare elements, is in harmony with the field relations. This late differentiate might have been introduced either as a relatively concentrated magmatic fluid, highly charged with volatile constituents such as carbon dioxide, sulfur, and fluorine, or as a dilute hydrothermal fluid.

INTRODUCTION

In April 1949 a vein containing considerable quantities of bastnaesite, a fluocarbonate of rare-earth metals of the cerium group, was discovered in the vicinity of Mountain Pass in eastern San Bernardino County, Calif. (fig. 1). Small quantities of this rare mineral have been noted at several localities in the United States, but this deposit was the first at which the mineral was sufficiently abundant to offer promise as a commercial source of rare-earth metals. The district is now known to contain a large supply of the rare-earth elements, and barium, strontium, thorium, and minor quantities of other metals.

The rare-earth metals are used primarily in the form of an alloy called misch metal, a mixture of several rare-earth metals of the cerium group. The principal current uses of the metals depend upon their pyrophoric properties. The rare earths are used in arc lamps, tracer bullets, in the flints of pocket lighters

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and carbide lamps, in the manufacture of gas mantles, and as deoxidizing agents in metallurgy. They have shown promise in alloys of light metals and in steel. Chemical compounds of rare earths have a wide variety of uses in industry. Several of the rare earths are excellent absorbers of slow neutrons, and their poisoning effect on the action of nuclear-energy piles has stimulated intensive study of the metals by the Atomic Energy Commission.

The rare earths have largely been obtained from monazite placer deposits in various parts of the world, chiefly from beach sands in India and Brazil, but only small quantities of monazite have been produced in this country. Bastnaesite had been known previously from only about 10 localities in the world. A little bastnaesite was mined in the late nineteenth century at Bastnäs, Sweden, and small amounts have been obtained from placer deposits in Belgian Congo and from deposits in central New Mexico.

During the period of 1949–51, exploration was intensive but only a few tons of bastnaesite ore were mined at Mountain Pass for metallurgical tests. Many pits and bulldozer excavations, commonly 5 to 10 feet deep, have been made in extensive search for rare-earth minerals. Only two mine workings in the district, the old Sulphide Queen gold mine and the Birthday shaft made in bastnaesite exploration, are as much as 100 feet deep. Present activity (1952) is largely confined to quarrying and drilling at the Sulphide Queen deposit.

LOCATION AND SURFACE FEATURES

The Mountain Pass district is an area about 7 miles long and 3 miles wide centered near Mountain Pass, 60 miles southwest of Las Vegas on U. S. Highway 91, near the northeast corner of San Bernardino County, Calif. (fig. 1). Most of the district is readily accessible from the main highway by dirt roads. The district is 16 miles by paved highway west of Nipton, Calif., a station on the Union Pacific Railroad. Altitudes range from about 4,000 feet at Wheaton Springs to slightly more than 6,000 feet on Kokoweef Peak and the Mescal Range. Clark Mountain, just northwest of the district, dominates the terrain; its altitude is 7,903 feet. The surface east of Wheaton Springs slopes within a few miles to the floor of Ivanpah Valley, about 2,595 feet in altitude. Mountain Pass, which has an altitude of 4,730 feet, is the highest point on Highway 91 between Las Vegas and Los Angeles.

The district is in part a rolling upland about 5,000 feet in altitude, which is part of a mature surface of moderate relief that has been referred to as part of the Ivanpah upland (D. F. Hewett, 1950, personal communication). Several peaks and ridges in the district rise about 1,000 feet above this surface. The eastern part of the district is chiefly a rugged, dissected terrain between the Ivanpah upland and the slope into the wide, alluviated Ivanpah Valley. Rock exposures generally are good. The central part of the district, near Mountain Pass, is partly obscured by gravels and alluvium. The gravels are several hundred feet thick in places and have been dissected so that ridges several hundred feet high are composed entirely of gravel deposits. The gravels contain blocks and fragments of the pre-Cambrian gneiss, Paleozoic limestone, dolomite, and quartzitic sandstone, Mesozoic sandstone and volcanic rocks, and igneous rocks, all in various proportions depending upon their distances from the sources of these materials.

The climate is arid. The district is dotted with juniper and joshua trees, and piñon are found near the north end of the district and on Clark Mountain. Water is scarce, rainfall is scant, and the principal sources of water are the springs. Waring (1919, p. 76–77) gives data on the water at Mexican Well and at Mescal, Roseberry, Mineral, and Wheaton Springs in the Mountain Pass district.

FIELD WORK AND ACKNOWLEDGMENTS

The Ivanpah 1°-quadrangle, which includes Mountain Pass near its center, was mapped by D. F. Hewett during the period 1924 to 1929. After the discovery in April 1949 of radioactive deposits and bastnaesite, the area of about 900 by 1,500 feet around the discovery (pl. 10), including the Birthday shaft (pl. 11), was mapped at 50 feet to the inch by W. N. Sharp and L. C. Pray between November 15, 1949, and January 20, 1950 (Sharp and Pray, 1952).

The geologic mapping of the district was done by J. C. Olson between August 3 and December 7, 1950, with the assistance of E. D. Jackson during August. Aerial photographs were used in the field mapping, and the geology was transferred to a planimetric base compiled from the photographs by the U. S. Geological Survey (pl. 1).

The Sulphide Queen carbonate body was mapped by W. N. Sharp and J. C. Olson during late October and November 1950, at a scale of 100 feet to the inch. During October, November, and December 1951, D. R. Shawe added details to this map and also mapped the area between it and the Birthday area.

Detailed investigation of the thorium resources of the district was made by D. R. Shawe between May 13 and June 17, 1952, with the assistance of W. N. Sharp from May 19 to June 4, 1952. Field work consisted of the mapping of several properties by plane table and compass-and-pace methods and sampling for analytical and petrographic study. This study of thorium re-

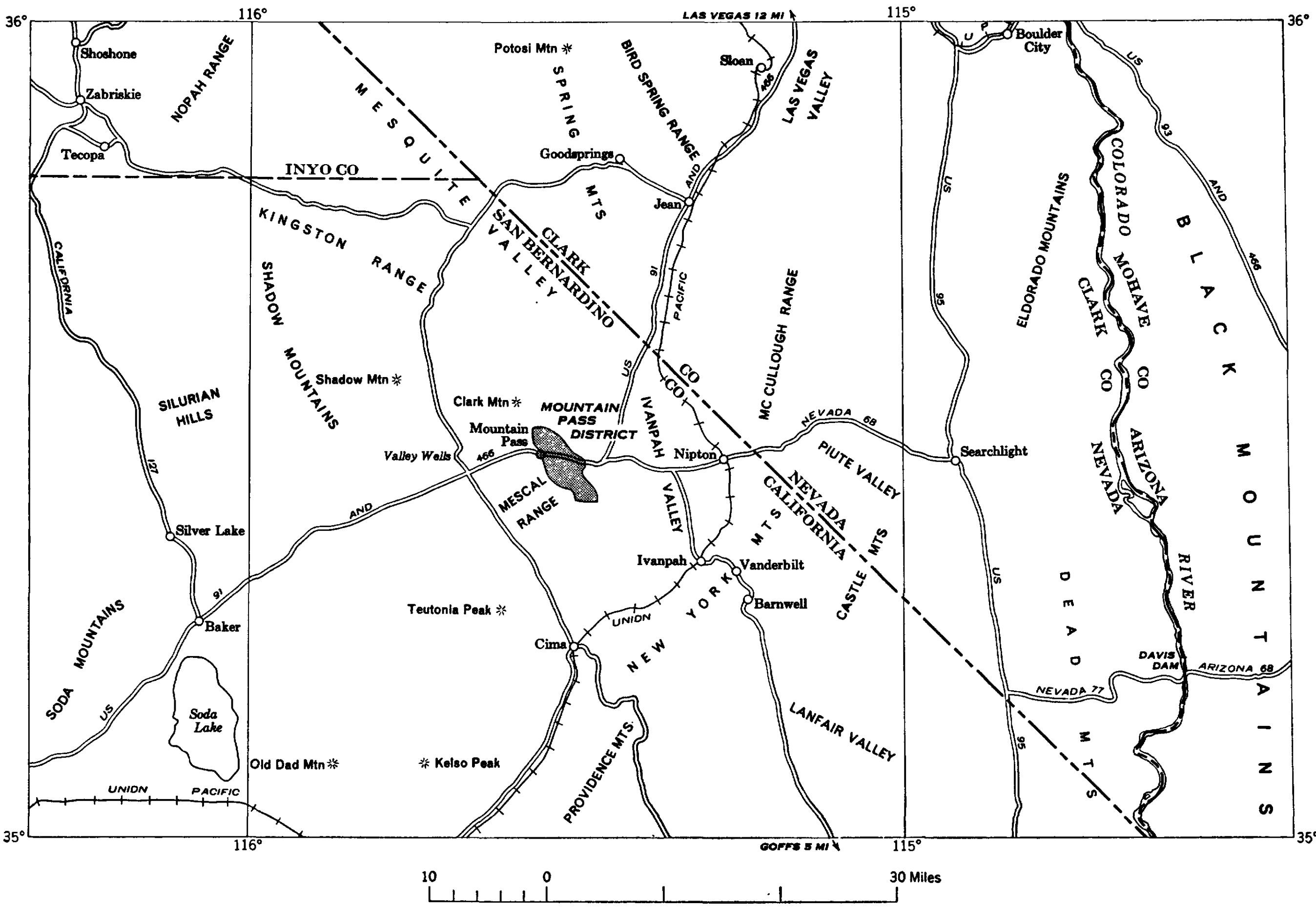


FIGURE 1.—Index map showing location of the Mountain Pass district.

sources, as well as the first investigation of the Birthday area, was made by the U. S. Geological Survey on behalf of the Division of Raw Materials of the Atomic Energy Commission.

Many U. S. Geological Survey geologists have contributed to the Mountain Pass studies through field conferences, discussions, and laboratory investigations. Particular acknowledgment is made of the counsel and general supervision of D. F. Hewett, W. T. Pecora, W. C. Smith, and L. R. Page. D. F. Hewett guided the investigations, contributed much regional geologic information from his work in the Ivanpah quadrangle, and prepared the discussion of history of the Mountain Pass discoveries which appears as a foreword to this report. W. T. Pecora made many helpful suggestions during the field and laboratory work and during the preparation of this report.

Chemical and spectrographic analytical work has been done during the course of the project by both the Denver and Washington laboratories of the U. S. Geological Survey. Mineralogical work on some of the first samples from the Birthday area was done by Jewell Glass and M. F. Deul. A systematic mineralogical and geochemical investigation of the district was begun in August 1951 by H. W. Jaffe, under the direction of W. T. Pecora. Some of the results of Jaffe's work on samples collected by himself or others are included in this report and additional data have been published (Jaffe, Meyrowitz, and Evans, 1953).

Prospectors and others in the district have given valuable assistance and information. Representatives of the Molybdenum Corporation of America, who have prospected intensively in the district, have extended many courtesies throughout the investigation.

This report incorporates field and petrographic data from all the sources named above. Throughout the report, data for the Sulphide Queen carbonate body, the intervening area (see pl. 4) between that and the Birthday claims, and descriptions of several claims have been prepared by D. R. Shawe. Petrographic and field data from the Birthday area, which appear in various parts of the report, have been prepared by L. C. Pray and W. N. Sharp. General geologic data for the district as a whole, and comparison with other areas, have been the responsibility of J. C. Olson. The section on origin of the deposits embodies ideas of all the authors.

GEOLOGY

The mountain range that extends north-northwest through Mountain Pass comprises the Ivanpah Mountains, the Mescal Range, and the mass of which Clark Mountain is the dominant peak. Sedimentary rocks form the higher, more resistant western half of the mountain range, and the older metamorphic rocks form the eastern half (fig. 2).

The rare-earth deposits in the Mountain Pass district have been found in a block of metamorphic rocks of pre-Cambrian age 4 to 5 miles wide and about 18 miles long in a north-northwest direction (Hewett, in preparation). This metamorphic complex is bounded on the south and east by the alluvium of Ivanpah Valley, and by faults on the east and west sides. The wedge of pre-Cambrian rocks tapers to a point at the north end where the bounding faults converge.

Within the block of metamorphic rocks, rare-earth minerals have been found in a segment 6 miles long in which potash-rich igneous rocks of probable pre-Cambrian age occur. The area shown in plate 1, about 7 by 3 miles, includes all the known rare-earth mineral deposits and will be referred to as the district throughout this report.

The normal fault that bounds the district on the west has been named the Clark Mountain fault by Hewett (in preparation). West of the fault lies about 8,500 feet of limestone and dolomite of Paleozoic age, overlain by about 4,000 feet of Mesozoic rocks (pl. 1). The Mesozoic rocks include thick, dark-red to brownish, volcanic flows and breccias that Hewett (1950, personal communication) has reported to be chiefly dacitic in composition and probably Cretaceous in age, inasmuch as they rest upon sandstone correlated with the Navajo

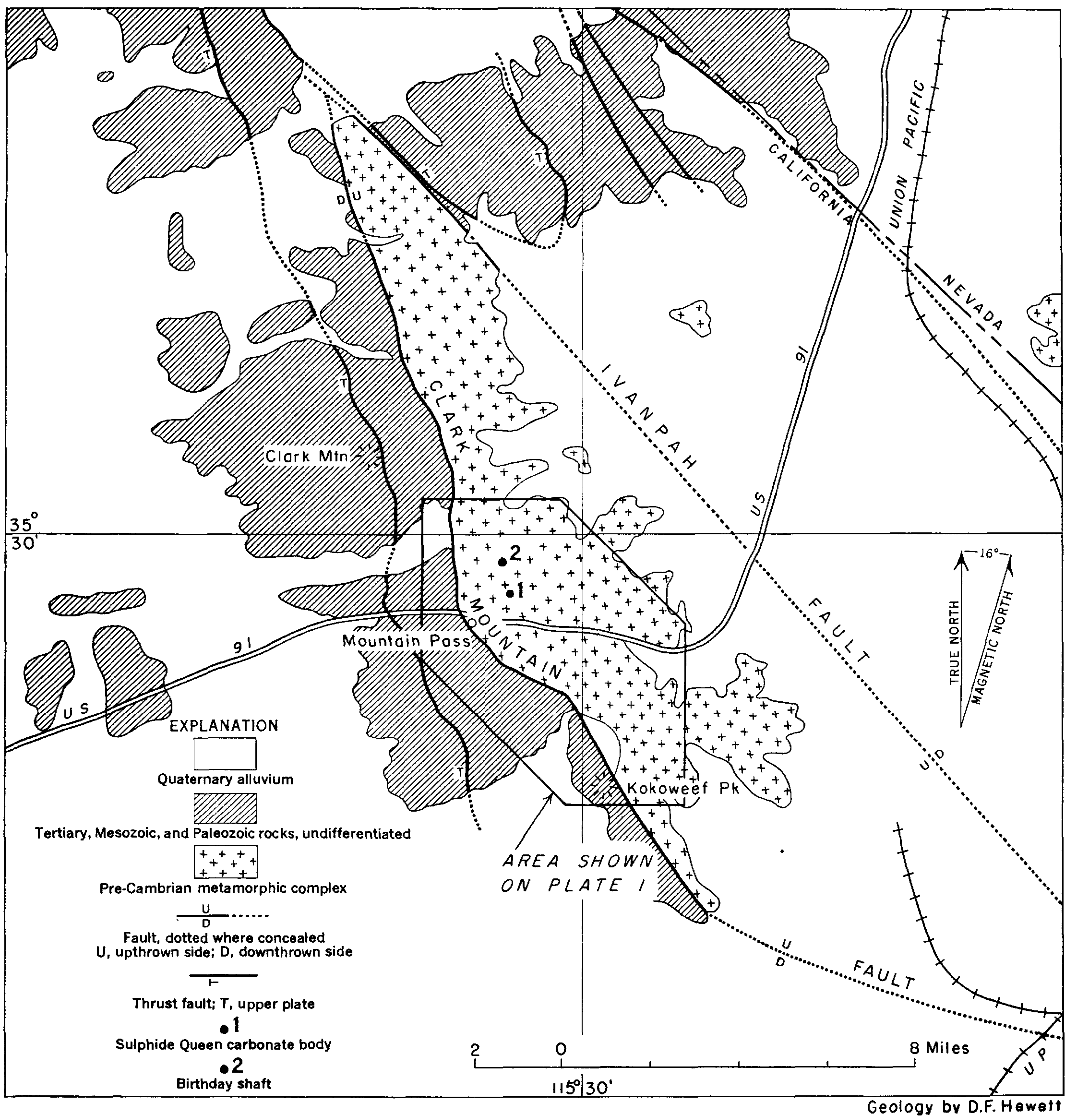


FIGURE 2.—Map showing regional geologic features of the Mountain Pass district.

sandstone of Jurassic age. These rocks on the west side of the fault are downthrown as much as 12,000 feet relative to the pre-Cambrian rocks exposed by erosion east of the fault. Movement occurred on the Clark Mountain fault after the potash-rich intrusive rocks and the rare-earth-bearing veins were emplaced; thus the absence of these rocks at the surface west of the fault is attributable largely to the magnitude of the displacement.

The normal fault that bounds the block of metamorphic rocks on the east has been called the Ivanpah fault (fig. 2) and the rocks east of this fault have dropped at least 10,000 feet, largely in Pleistocene time (Hewett, in preparation). The Ivanpah fault is obscured by alluvium throughout most of its inferred length.

The district is bounded on the north by a fault, trending N. 70° W., which displaces the Clark Mountain fault. Syenitic dike rocks and rare-earth-bearing veins are abundant immediately south of this cross-fault, but none have been found in the pre-Cambrian rocks that extend 10 miles north of it.

Several large, west-dipping low-angle thrust faults have been mapped by Hewett west of the Clark Mountain fault. From the fact that the Clark Mountain fault cuts several early thrusts, and is in turn overridden by a later thrust fault north of the district, Hewett (in preparation) has concluded that the Clark Mountain fault is an interthrust normal fault and, like the thrusts, is a feature of the Laramide orogeny of this region.

PRE-CAMBRIAN METAMORPHIC ROCKS

Pre-Cambrian rocks in the eastern Mojave region of California and southern Nevada (see for example Hewett, 1931, p. 10–11; Nolan, 1943, p. 145–146; Hazzard and Dosch, 1936, p. 308–309) have been divided generally into an older pre-Cambrian group of gneisses and schists with some granitic rocks, and a younger group of predominantly metasedimentary rocks. There is no indication that any of the younger metasedimentary rocks are present in the Mountain Pass district, and the gneisses and schists are therefore considered to be of greater pre-Cambrian age. The pre-Cambrian metamorphic rocks that underlie most of the Mountain Pass district are well foliated in contrast to the igneous rocks that intrude them. The foliation strikes N. to N. 30° W. and commonly dips 50°—80° W. (pl. 1).

GNEISSIC COMPLEX

The various metamorphic rocks are so intricately interlayered that at the scale of the district mapping it was found practicable to delineate rock units only on the basis of relative proportions of the different types. Accordingly, on the map showing divisions of the metamorphic complex (fig. 3), the contacts between formations represent gradations in the relative proportions of diverse rock types rather than sharp changes in lithology.

Unit A of figure 3, which will be referred to as biotite granite gneiss complex, is composed chiefly of biotite granite gneiss in small and large masses, as much as 1,000 feet wide, with only minor bands of other gneisses. The biotite gneiss has conspicuous augen or rectangular grains of potash feldspar, as much as 1 inch long and commonly carlsbad-twinned, in a fine-grained matrix of feldspar, quartz, and biotite. This biotite gneiss is distinctly foliated and locally schistose, because of the parallel orientation of biotite flakes and potash feldspar grains, and the layering due to segregation of light and dark minerals. Another variety, a biotite-hornblende gneiss, is locally injected by the light-colored granitic augen gneiss and pegmatites, and may be related to the biotite granite gneiss. The biotite granite gneiss in the thin dikelike bodies, most of which are concordant, is generally more schistose than that in the larger masses. Some of the thin bodies are finer grained near their margins than in their centers.

The masses of biotite gneiss grade outward into mixed gneisses in which thin layers of the biotite granite gneiss, a foot or several feet thick, alternate with bands of older layered gneisses, such as biotite schist and gneiss, in part garnetiferous; coarse-grained biotite-garnet-sillimanite gneiss; hornblende gneiss and schist, and amphibolite, with varying amounts of biotite, chlorite, and augite; and quartz-mica schist. These dominantly layered or banded rocks, which may be at least partly metasedimentary or metavolcanic in origin, appear to be invaded by both the biotite granite gneiss and the light-colored granitic augen gneiss, although the latter is uncommon in unit A.

Unit B (mixed granitic gneiss complex), is essentially a transition zone between units A and C, composed of the rocks of unit A, together with the light-colored granitic augen gneiss. The granitic augen gneiss on the average constitutes less than half the total rock of unit B, forming thin concordant bands and, more rarely, crosscutting dikes.

Unit C (granitic augen gneiss complex) on the map of the metamorphic complex (fig. 3) consists dominantly of light-colored granitic augen gneiss in which are thin layers or larger masses many feet thick of the hornblende gneiss and schist, biotite schist, and other rock types of unit A. Some areas several hundred feet or more wide are almost entirely granitic augen gneiss, but in most places the rock is a migmatite con-

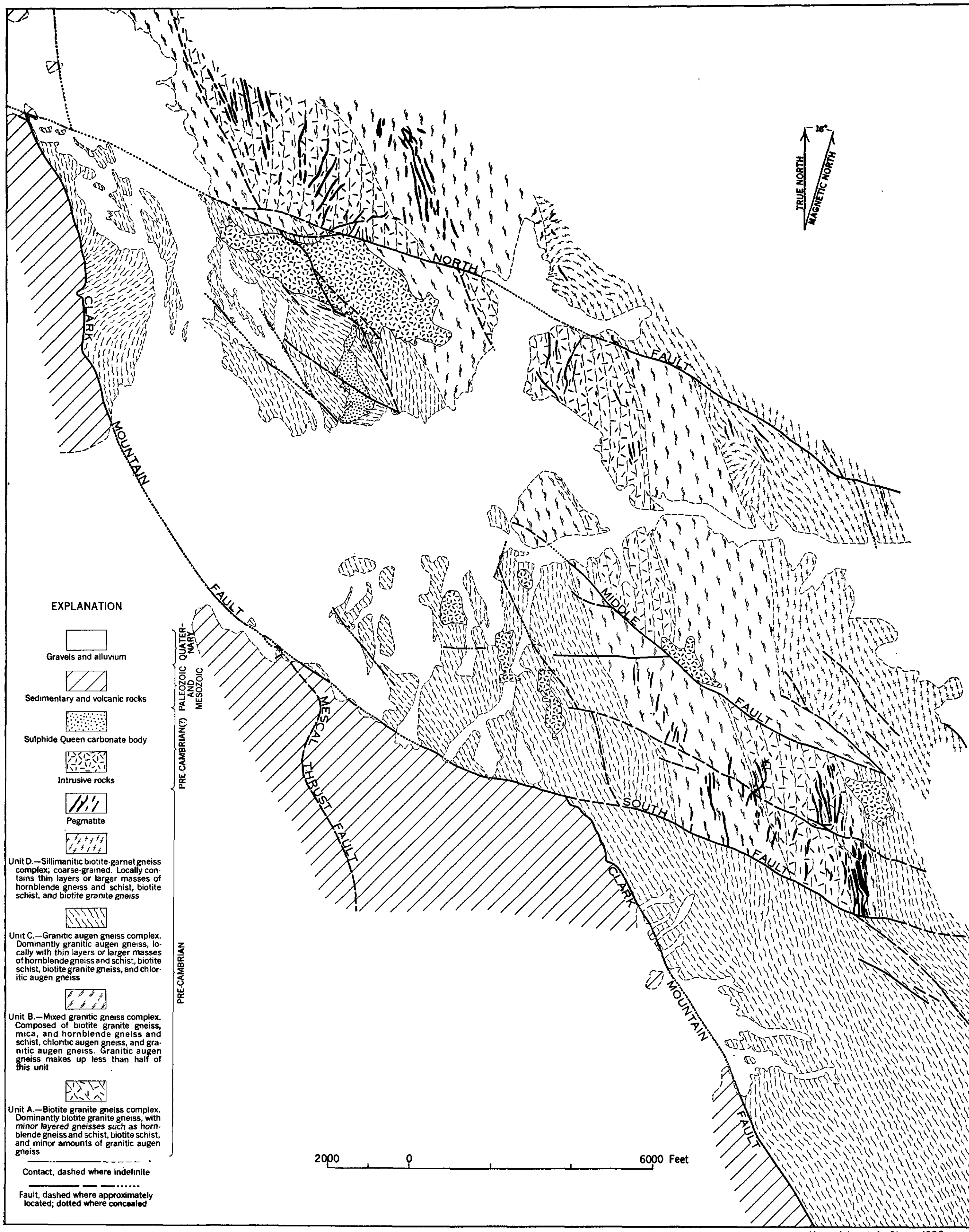


FIGURE 3.—Generalized map of metamorphic complex, Mountain Pass district.

taining thin layers of other gneisses permeated by granitic material. Individual bands of hornblende gneiss or schist, biotite schist, biotite-garnet gneisses, or chloritic granite gneiss in this migmatite, although of the order of 100 feet wide in many places, are not persistent and can be traced only with difficulty, and it is impractical to delineate them at the scale of the district map. In some places the layers of the migmatite are only an inch or two thick. Garnet and sillimanite are present in some layers in the area of unit C, but are less abundant than in unit D. Hornblende, biotite, and garnet are commonly altered to chlorite, and epidote is locally conspicuous in unit C.

The granitic augen gneiss, which is the most abundant rock type in unit C and in the district as a whole, consists chiefly of pink to white feldspar and quartz, with very little of the dark minerals. The gneiss is fine to very coarse grained. The dominant constituent is perthitic potash feldspar, which makes up about half the rock, chiefly as augen of orthoclase or microcline, in places as much as 3 cm long and 1 cm thick enclosed in a finer grained matrix of quartz with lesser amounts of plagioclase and sericite. Quartz constitutes 30 to 40 percent of the average granitic gneiss, commonly forming thin films or streaks along foliation planes. Dark minerals are practically absent, although minor hematite and opaque minerals constitute 1 to 3 percent, and biotite, in part altered to chlorite, forms several percent of parts of the gneiss. Sericite and epidote are present as alteration products. Garnet is common in many areas of granitic augen gneiss and is most abundant in those in which the granitic augen gneiss alternates with and grades into layers of other metamorphic rocks forming migmatite. The degree of development of the augen structure of the granitic gneiss varies in different places.

A chloritic variety of augen gneiss is most abundant in units B and C, chiefly as thin layers but also as the principal constituent of areas several hundred feet wide. This chloritic augen gneiss contains pink or white feldspar augen which generally constitute 30 to 40 percent of the rock. Quartz films and streaks parallel the foliation and make up as much as 50 percent of the rock. Between the feldspar augen is a greenish, fine-grained aggregate of chlorite, epidote, magnetite, hematite, muscovite, zircon, and apatite. Carbonate veinlets occur locally in late fractures, and sericite occurs as an alteration product of feldspar. Most of the chloritic augen gneiss is granitic to granodioritic in composition. The feldspar is orthoclase chiefly, with minor albite, but some of the rock contains plagioclase as calcic as andesine as the principal feldspar of the matrix. Little petrographic study has been made of these variations. The chlorite and magnetite are probably derived chiefly through the alteration of biotite; garnet is also largely altered to chlorite. Some of these rocks with only a small amount of chlorite may be altered facies of the light-colored granitic augen gneiss. In other places the chloritic augen gneiss may represent strongly sheared and altered biotite gneiss in zones which were much injected by later light-colored granitic augen gneiss.

Unit D (sillimanitic biotite-garnet gneiss complex) on the map of the metamorphic complex is characterized by coarse-grained to pegmatitic biotite-garnet-sillimanite gneiss containing abundant coarse granitic material in streaks along the foliation and in larger bodies. Like the other units, unit D is variable and contains bands of various other layered metamorphic rocks. It is separated from unit C chiefly because of its coarse grain size and the more widespread occurrence of sillimanite in unit D. Garnet and biotite grains are as much as an inch in diameter. Foliation is well-developed but irregular in detail, and small folds and crenulations are characteristic features. Because of the metamorphism and the impregnation by granitic material, the origin of the coarse-grained gneiss is obscure. Interlayering and the presence of sillimanite and garnet in some layers suggest a metasedimentary origin in part. The garnet in the granitic material may be due to contamination by the older layered gneisses. This is suggested by the local occurrence of garnet in pegmatitic granite gneiss within a few feet of a mass of garnet-biotite-sillimanite gneiss, and its scarcity in the same rock in a large area away from the inclusion.

PEGMATITES

Pegmatites of simple granitic composition occur in many parts of the district. They are as much as 125 feet wide and some are more than 1,000 feet long. Some of the largest are shown on the geologic maps (fig. 3 and pl. 1). The largest pegmatites (fig. 3) are found chiefly in the areas of mixed granitic gneiss complex (unit B).

The pegmatites consist chiefly of pink to white potash feldspar and quartz, with minor gray to white plagioclase, muscovite, and rare garnet. Zoning or gross segregation of minerals is not noticeable, except random thin streaks of quartz generally less than a foot thick. The granitic pegmatites appear to be related chiefly to the light-colored granitic augen gneiss, as suggested by the similarity in composition, close spatial relationship, and gradation in grain size between the two types. Where older gneisses or schists are thoroughly permeated by granitic material, pegmatitic granite alternates with finer grained granite layers apparently differing only in grain size. In other places, the pegmatites are distinctly later than the granitic material, as shown by sharp, discordant contacts and slight differences such as pink potash feldspar in the pegmatite, as opposed to white potash feldspar in the granitic gneiss. The pegmatites are commonly somewhat gneissose, and have been affected by pre-Cambrian metamorphism.

MAFIC ROCKS

Hornblende gneiss and schist, and amphibolite, occur in many parts of the district, and some rocks of more mafic composition such as peridotites are known. Some of the layered hornblendic rocks are probably of sedimentary or volcanic origin, but others are probably intrusive into the banded gneisses, as suggested by their occurrence in small oval patches or dikelike bodies. Some of these mafic rocks are cut by thin dikes of the granitic gneisses. Others are probably younger, as some mafic gneisses locally contain broken fragments of granitic gneiss, and pegmatite appears to be cut by at least one hornblende gneiss band.

The mafic rocks are both fine- and coarse-grained, and are locally recrystallized near thin dikes of granitic gneisses. Many are of generally dioritic composition, containing hornblende and plagioclase, with minor augite, quartz, and sphene. Several small bodies of more mafic rocks also occur. Thin sections were made of serpentinized gabbro or peridotite from two well-foliated bodies of mafic rock, the larger being about 75 by 150 feet in plan. These rocks are composed of about 30 to 35 percent clinopyroxene, 40 to 45 percent serpentine, and the remainder of olivine, opaque minerals, and minor chlorite, muscovite, and spinel. Serpentine appears to have formed from both olivine and the clinopyroxene. Many of the dioritic and more mafic rocks are altered, and minerals such as chlorite, epidote, calcite, and serpentine are common alteration products of hornblende, garnet, feldspar, biotite, pyroxene, or olivine.

STRUCTURE

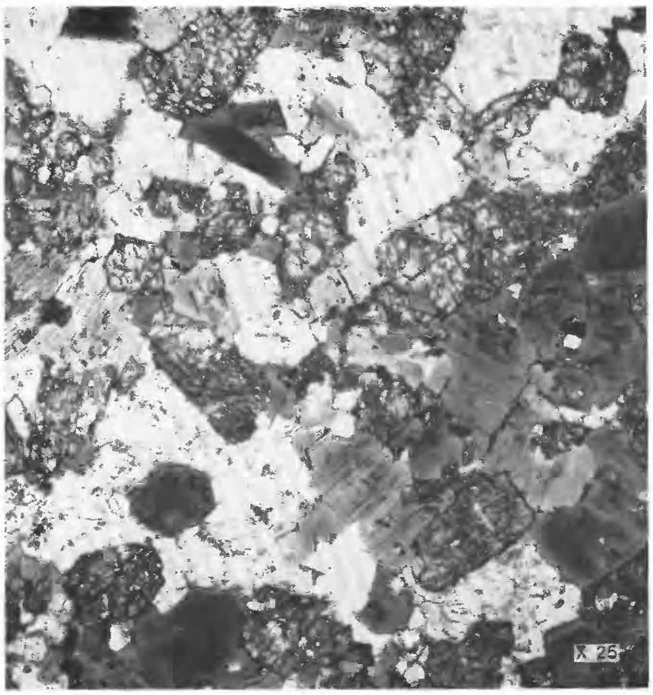
All the metamorphic rocks have a foliation which strikes on the average N. to N. 30° W., parallel in general to the Clark Mountain fault, to the long dimension of the block of pre-Cambrian rocks, and to the individual layers or rock units in the pre-Cambrian terrain (pl. 1). The foliation dips 50°–80° W. in much of the area. Local deviations from the general trend are common; for example those near the large carbonate body a mile northeast of Mountain Pass and near the potash-rich intrusives. Minor folds and crenulations are particularly common in the area designated as unit D, the coarse-grained biotite-garnet-sillimanite gneiss (fig. 3).

Local concentrations of drag folds or crenulations in several places suggest possible zones of pre-Cambrian movement parallel to the general trend of the foliation. For example, a zone 30 to 40 feet wide, about 6,000 feet N. 56° E. of Mexican Well, contains abundant drag folds, plunging 40° N., in the pegmatitic garnet-biotite gneiss. This zone parallels the regional foliation and is cut by an east-trending Tertiary andesitic dike that is not displaced.

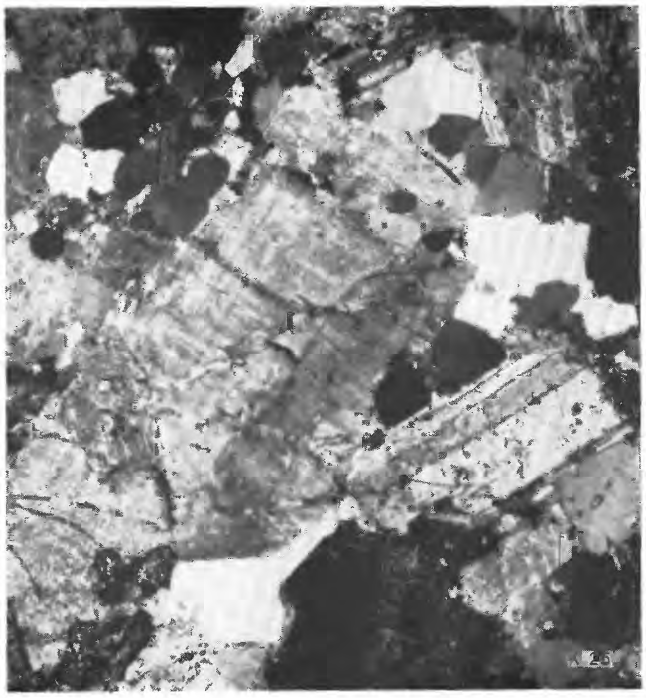
Pre-Cambrian breccias, composed of fragments of granitic gneiss in dark gneiss and of fragments of dark gneiss in granite, have been observed in a few places, and are considered to be products of deformation of the gneiss during pre-Cambrian time.

Within a few feet of most of the faults that cut the gneisses, the foliation is commonly dragged to approximate parallelism with the faults, and this drag is one of the criteria used in tracing faults. Near the faults, the plagioclase is commonly saussuritized and minerals such as hornblende and garnet are commonly altered to chlorite, epidote, opaque minerals, and calcite. In the gneiss near the aviation beacon, for example, this chloritic alteration is conspicuous over a width of more than 1,000 feet, and increases near the Clark Mountain fault. In some places near the Clark Mountain fault, chlorite and epidote occur on closely spaced shear planes, approximately parallel to the fault, that impart a second foliation not necessarily parallel to the pre-Cambrian foliation.

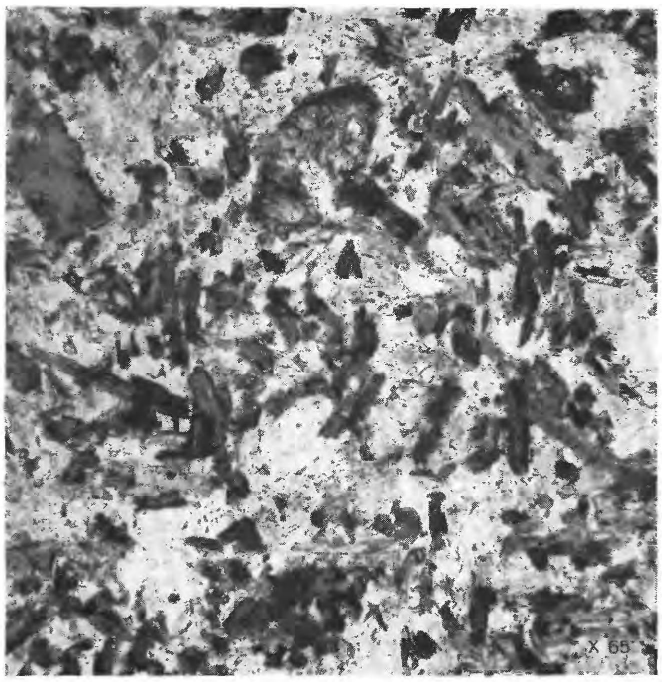
Many of the metamorphic rocks have a lineation that in most places plunges in a direction a little south of west, almost downdip, commonly at angles of 55° to 70°. The lineation is due to the orientation of hornblende needles or elongate grains of such minerals as feldspar, mica, or epidote, elongate bunches of biotite flakes or trains of micaceous minerals, fracture intersections, and minor folds or crenulations. The lineation is found in some of the youngest of the metamorphic rocks, such as the dikelike masses of hornblende gneiss. The foliation and lineation were very likely not all produced at one time, but are the composite result of different types and degrees of metamorphism occurring during a long pre-Cambrian history. For example, many pegmatites appear to have been injected along a preexistent planar structure, yet the pegmatites themselves are commonly foliated, although not so conspicuously as the other rocks because of their coarse grain size. The foliation in the pegmatites commonly parallels that in the adjacent wall rocks, even in those pegmatite bodies that are sharply discordant to the gneissic foliation. A few thin dikes of hornblendic gneiss and amphibolite cut across pegmatites and granitic augen gneiss and these, too, have a foliation ap-



A. Shonkinite (predominantly potash feldspar, biotite, and augite). Crossed Nicols.



B. Granite. Crossed Nicols.



C. Shonkinitic dike rock. Plane polarized light.

L. C. Pray

D. Bastnaesite crystals in carbonate rock, Birthday area.

PHOTOMICROGRAPHS OF ROCKS AND MINERALS, MOUNTAIN PASS DISTRICT, CALIFORNIA

proximately parallel to that of their wall rocks even though the bodies are discordant to this foliation.

AGE RELATIONS AND ORIGIN

The age relations of rocks forming the metamorphic complex are not known completely, but generally the granitic augen gneiss, which forms the greater part of unit C, (fig. 3) and is the most abundant rock type in the district, permeates the other principal rock units and locally forms crosscutting dikes. Generally, the permeation by this granitic material, forming migmatite, was least in unit A (biotite granite gneiss complex), greater in units B and C, and greatest in unit D where coarse pegmatitic gneisses with sillimanite are found. Accordingly, one might conjecture that unit A forms a pendant of older gneisses, containing only minor amounts of the light-colored granitic augen gneiss, bounded on both sides by migmatite or injection gneiss of units C and D containing greater amounts of the granitic augen gneiss. Unit B, the mixed granitic gneiss complex, forms a transitional zone, containing about 10 to 50 percent granitic augen gneiss, between unit A and units C or D.

The occurrence of the largest pegmatites chiefly in the areas of mixed rocks between units A and C harmonizes with this hypothesis that Unit A forms a pendant of older gneisses surrounded by predominantly migmatite and granitic gneisses, inasmuch as pegmatites are expectable in injection zones marginal to the migmatite and granite gneiss areas. The pendant represented by unit A seems to thin southward. It is displaced by cross faults, and was not delineated south of the South fault, where intermixed granitic augen gneiss is more abundant.

The origin of the metamorphic complex is not known. The layered rocks of contrasting compositions may well have been sedimentary or volcanic in part. The granitic gneisses may have formed by the permeation of granitic material through older rocks; they may in part be magmatic; or they may in part represent sedimentary rocks converted to granites. Some of the metamorphic rocks, particularly certain mafic rocks and pegmatites, are crosscutting dikes intruded after most of the complex had formed but old enough to have been affected by some of the metamorphism.

Variations in the metamorphic rocks may reflect original differences in composition, and different water content, and they may also reflect varying degrees of metamorphism in different parts of the district. For example, the conspicuous augen structure of much of the granitic gneiss may have developed at a time when the granitic material was partly fluid or mobile, localizing the deformation and recrystallization in certain layers. The crenulations and the coarse grain size of the sillimanite-bearing gneisses imply different conditions, perhaps greater temperature or pressure, or different water content, in their formation than in the more evenly layered gneisses in other parts of the district.

IGNEOUS ROCKS

Essentially nonfoliated igneous rocks intrude the metamorphic complex of pre-Cambrian age. In age, composition, and distribution they are divided into two general groups: an older group of potash-rich rocks including biotite shonkinite, hornblende and biotite syenites, granite, and related dike rocks, and a younger group of generally andesitic dikes ranging in composition from basalt to rhyolite. The older, potash-rich dikes generally trend northwestward, whereas the younger dikes commonly trend eastward. The andesitic dikes are considered tentatively as Tertiary in age on the basis of regional evidence (Hewett, 1950, personal communication). The potash-rich rocks are younger than the pre-Cambrian foliation and older than the andesitic group of dikes. Age determinations of monazite and zircon indicate the potash-rich rocks and related carbonate rocks are of pre-Cambrian age.

The potash-rich igneous rocks occur in a belt about 7 miles long and 1½ miles wide extending from the transverse fault, about 2,000 feet north of Mohawk Hill, at least as far south as the limit of geologic mapping. Near the south end of the map area (pl. 1), the potash-rich dikes are thin and sparsely distributed, and they are probably scarce or absent in the interval of 2 or 3 miles between the southern map boundary and the alluvium of Ivanpah Valley. Within the district seven larger intrusive bodies, ranging from 300 to 1,800 feet in width, and several hundred thinner potash-rich dikes about 1 to 30 feet thick and as much as 3,500 feet long, have been mapped.

The more silicic of the intrusive bodies, especially those containing quartz, are relatively resistant to weathering and stand out as ridges and peaks. The biotite-rich dark intrusive rocks, however, are more friable than the other rocks, crumble relative easily on weathering, and commonly form gentle slopes. Jointing is conspicuous in some of the lighter-colored intrusive bodies, but the shonkinite is less jointed and decomposes into rounded masses by spheroidal weathering.

Shonkinite, syenite, and granite form dikes throughout the district. Most of the dikes are in general parallel with the foliation in the gneiss, and are concentrated near the seven larger instrusive bodies. On the average, the thin dikes, whether of shonkinite, syenite, or granite, are finer grained than the same rocks in the large bodies, and porphyritic varieties are abundantly represented in the dike rocks.

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Most of the thin dikes are essentially homogeneous throughout their extent, but a few are composite. A nearly vertical composite dike 6 to 9 feet thick is exposed for a length of 50 feet about 3,800 feet N. 85° W. of the Windy propects. This dike is made up partly of shonkinite or biotite-rich syenite but is largely hornblende syenite and leucosyenite. Another composite dike just south of the Mineral Hill granite body is 20 inches thick. The footwall half of this dike is light-colored biotite syenite, and the upper half is a slightly younger injection of finer grained quartz-bearing leucosyenite.

The sequence of intrusion of the igneous rocks is the same throughout the district, as shown by relationships in all the intrusive bodies described. The oldest of the potash-rich rocks is the shonkinite, which is generally coarse-grained. The shonkinite grades into and is cut by slightly later syenites, and these in turn are transected by still later, progressively finer grained syenite and granite. Dark dikes of shonkinite, finer grained on the average than the shonkinite of the larger stocks, cut the granite and are the youngest of the potash-rich rock sequence wherever the age relations are clearly established.

PETROGRAPHY

SHONKINITE

The term "shonkinite" in this report is used for rocks of the syenite clan containing more than 50 percent dark minerals. The name was first applied by Weed and Pirsson (1895, p. 415–416) to a melanocratic syenite in the Highwood Mountains of Montana, and they defined it as a "* * * granular plutonic rock consisting of essential augite and orthoclase, and thereby related to the syenite family. It may be with or without olivine, and accessory nepheline, sodalite, et cetera, may be present in small quantities." The average mode reported by Pirsson (1905, p. 104) is listed in table 1. Although the type shonkinite of the Highwood Mountains contains minor nepheline, the feldspathoid is not an essential constituent as defined by Weed and Pirsson. Later detailed petrographic studies of shonkinite in the Highwood Mountains have been published by Barksdale (1937), Larsen and Buie (1938), and by Larsen, Hurlbut, Buie and Burgess (1941).

The shonkinite at Mountain Pass is a distinctive, dark-colored rock composed largely of grayish-red microcline, green augite, and biotite (pl. 2*A*). Modal analyses of the shonkinite of the Birthday area (pl. 10) are given in table 1. Dark minerals form rarely as much as 70 percent and more commonly about 50 percent of the shonkinite of the Mountain Pass district. Biotite-rich syenites containing 30 to 50 percent mafic minerals are also common.

TABLE 1.—*Modal analyses of shonkinite from the Birthday area.*

	A	B	C	D	
				Parallel to foliation	Perpendicular to foliation
Microcline [1]	24.5	24.6	26.0	34.9	44.6
Pseudoleucite(?)			9.3		
Biotite	33.3	40.9	21.3	40.6	34.9
Augite	37.5	29.3	36.2	15.6	11.3
Apatite	4.0	4.0	3.6	4.7	4.1
Iron oxides	.5	1.2	3.5	(2)	(2)
Olivine (resorbed)				1.5	3.4
Others	.2		.1	2.7	1.7
Specific gravity				2.94	2.94

[1] Includes microperthite.
[2] Included in "Others."

A, B, and C analyzed by L. C. Pray.
D collected by T. B. Nolan; modal analysis by H. W. Jaffe.

Type shonkinite, Highwood Mountains, Montana (*Pirsson, 1905, p. 104*)

Alkalic feldspar [1]	20	Olivine	10
Nephelite	5	Biotite	8
Sodalite	1	Iron ore	6
Augite	46	Apatite	4

[1] Considered sanidine by Larsen, Hurlbut, Buie, and Burgess (1941).

BIOTITE

The most abundant dark mineral is coarse lustrous biotite, in flakes as much as 0.5 inches in diameter, which constitutes 25 to 40 percent of most of the shonkinite; hence the rock is biotite shonkinite. In thin section the biotite is dark red-brown, pale brown, and locally green. The intermediate index of refraction of some of the biotite has been determined as 1.618 ± 0.002. The biotite is commonly dotted with iron oxides. Pleochroic halos are present but not abundant. Some of the biotite crystals enclose small euhedra of augite and apatite. Small flakes of biotite are enclosed poikilitically in the coarse- to medium-grained potash feldspar. Locally the biotite flakes tend to parallel one another, but in nearly all the shonkinite the biotite flakes have random orientation.

The biotite is green in parts of some thin sections and grades to yellowish-brown outside these areas. The color change may occur within a single biotite crystal, and a few of the biotite crystals have green fringes which may be late reaction products. In one thin section, the yellowish-brown biotite is associated with soda-poor and soda-rich amphibole, but the green biotite occurs only in the vicinity of the soda-bearing type, suggesting that the color variation is associated with the development of soda-amphibole. In another thin section of shonkinite near the Sulphide Queen carbonate body, the alteration of biotite seems related to replacement of parts of the rock by potash feldspar. This thin section of altered shonkinite, taken from a shear zone (1905 S., 374 W. on the map grid, pl. 4), consists of about 35 percent biotite; 35 percent augite, in part altered to epidote, fine-grained iron oxide, and feldspar (?); 25 percent orthoclase; and 3 to 4 percent accessory apatite. The altered augite and the carbonate minerals along seams are probably associated with the period of shearing. Large, irregular, optically continuous patches of orthoclase are scattered throughout the section and cut indiscriminately across the biotite and other minerals. Peripheral to the orthoclase patches the biotite is green in contrast to the orange-brown biotite away from the patches. Some mica crystals grade toward the orthoclase from orange-brown biotite through green biotite to colorless mica (pl. 3). Centers of the orthoclase patches commonly contain skeleton crystals of muscovite, small parts of which are green. The muscovite has 2V of approximately 35°.

PYROXENE AND AMPHIBOLE

Pyroxene and amphibole are next to biotite in abundance among the mafic minerals and constitute 5 to 40 percent of the shonkinite. Augite, aegirine-augite, and hornblende predominate among the minerals of these groups, but aegirine and soda-amphiboles such as riebeckite and arfvedsonite are widespread.

The dominant pyroxene of the shonkinite is pale-green augite. The following optical properties have been determined for augite in shonkinite from the Birthday area: $n\text{Y}=1.685\pm0.005$; birefringence 0.025 ± 0.003; 2V estimated as 60°–70°; biaxial positive; $c\wedge Z$ about 45°. Pleochroism is not evident in most of the pyroxene. Some crystals are bright green or have bright green fringes and high relief, and are considered to be aegirine-augite. Augite and aegirine occur, either separately or in the same rock, in small euhedral to subhedral grains as much as 0.3 inches long. The relatively early age of the augite in the rock is indicated by the evidence of its replacement by other minerals, poikilitic enclosures in potash feldspar, common euhedral form, and broken crystals cemented by mixtures of potash feldspar, biotite, and iron oxides. Augite crystals commonly are zoned parallel to crystal outlines.

The optical properties of aegirine in one shonkinite sample were determined by Robert S. Jones, of the Geological Survey, who contributed optical data on pyroxenes and amphiboles in three samples of shonkinite. This aegirine is biaxially positive, nX 1.758 and nZ 1.803 ± 0.003, with a small extinction angle.

Amphiboles are relatively widespread in the shonkinite but form only a small fraction of the mafic minerals. Dark-green common hornblende occurs in some of the rocks, soda-amphibole in others, and commonly both types are present. Within these groups there is a range in indices and color suggesting gradations in composition.

The common hornblende in thin section shows a range in pleochroic colors, typically yellow-green (X) to dark green or yellow-brown (Z). The birefringence is commonly about 0.020. The indices, determined for a few grains, range from 1.625 to about 1.68 (nX) and 1.64 to about 1.70 (nZ), suggesting a range in composition.

The soda-amphiboles are markedly pleochroic, in shades of blue, violet, and green. Some of the soda-amphibole has been identified as riebeckite, but the range in optical properties suggests that other soda-amphiboles are present also. In some crystal fragments, distinct color differences from blue in one part to green in another probably indicate differences in chemical composition within the fragment, the blue color possibly being due to greater richness in sodium. Spectrographic analysis of amphibole containing both the green and blue types indicates high sodium and low aluminum content, as in riebeckite. A few grains of the soda-amphiboles, immersed in index liquids, show a range in indices from 1.665 to 1.695 (nX) and 1.670 to 1.700 (nZ), birefringence about 0.005.

The soda-amphiboles occur as grains 0.25 inch or less in length, or as aggregates of grains, that appear to be primary constituents; and as alteration products of pyroxene or common hornblende. In some thin sections, aggregates of hornblende, magnetite, and calcite, representing a former mafic mineral, are surrounded by a kelyphitic reaction rim of sodic amphibole. Fibrous aggregates of soda-amphibole replace pyroxene or common hornblende. Some of the shear planes in the shonkinite and other rocks are lined with crocidolite (blue asbestos), with optical properties similar to riebeckite.

FELDSPARS

The potash feldspar, which makes up nearly half of the shonkinite, generally occurs in pale-red, grayish-red, or purplish-red anhedral grains 0.1 to 0.5 inch in diameter and exceptionally as much as 3 inches across. Some of the shonkinite has a poikilitic texture, in which the microcline grains enclose many smaller crystals of biotite, augite, apatite, and other minerals. In specimen D (table 1), large single masses of clear potash feldspar, as much as 3 inches across, poikilitically enclose other minerals. The potash feldspar (sanidine ?) in this specimen has a small to medium optic angle, in contrast to the large optic angle of potash feldspar in 20 or more other thin sections of shonkinite. On the basis of this sampling, sanidine is probably the exception rather than the rule in the Mountain Pass shonkinites. Microperthitic intergrowths of albite are common in the potash feldspars, but separate grains of plagioclase rarely exceed 10 percent of the rock and commonly constitute only 1 to 3 percent.

OTHER MINERALS

In one thin section of the shonkinite from the Birthday area about 10 percent of the rock consists of euhedral crystals that are suggestive in shape of leucite. These are altered to a cloudy mass of potash feldspar, sericite, and unidentified minerals of low birefringence and relief. These crystals and other similar appearing aggregates that lack the euhedral outlines are provisionally considered as pseudoleucite. The cloudy aggregates contain many small inclusions of iron oxides.

Olivine is a minor mineral that occurs locally in the shonkinite. It forms about 5 percent of the minerals in the one thin section where it was identified. Most crystals are nearly equant and almost completely altered to serpentine and iron oxide.

Accessory minerals in the shonkinite comprise sphene, leucoxene, zircon, epidote, olivine, and locally as much as 5 percent apatite or iron oxides. The accessories are commonly localized around and in the mafic minerals. Apatite, the most abundant accessory mineral, makes up 4 percent of the four rocks for which modal analyses were determined. The apatite crystals are commonly euhedral and 0.1–0.2 mm across, and as much as 1 mm long. They occur as inclusions in the augite, biotite, and microcline. Five thin sections of shonkinite from near the southwest contact of the shonkinite-syenite body northwest of the Sulphide Queen mine (pl. 4) were examined, and these are relatively rich in accessory minerals, commonly containing about 2 percent zircon, 2 to 5 percent apatite, and 2 to 3 percent sphene.

The shonkinite is characterized by textural variability. The rock is mostly medium-grained, but ranges from rock in which the crystals are less than 1 mm across to pegmatitic varieties with some crystals several inches across. The grain size in most of the shonkinite is 2 to 5 mm. Gradations between fine and coarse textures occur in distances of a few inches or a few feet. Patches of pegmatite, generally a few inches thick and only a few feet long, occur here and there with irregularly gradational contacts in the shonkinite. In the pegmatitic parts, potash feldspar commonly predominates, and mafic minerals are subordinate and less abundant than in the enclosing shonkinite. Soda-amphibole and aegirine are the common mafic constituents of the pegmatite, and sphene, zircon, allanite, and biotite are locally present.

Poikilitic texture is characteristic of much of the shonkinite, and is due to the enclosure of dark minerals such as biotite and augite in potash feldspar grains as much as 3 inches in diameter. Locally the shonkinite in the larger masses is porphyritic; phenocrysts of biotite and some augite or hornblende occur in a finer-grained ground-mass composed largely of potash feldspar with some dark minerals. Porphyritic texture is more common, however, in the thin shonkinitic dikes.

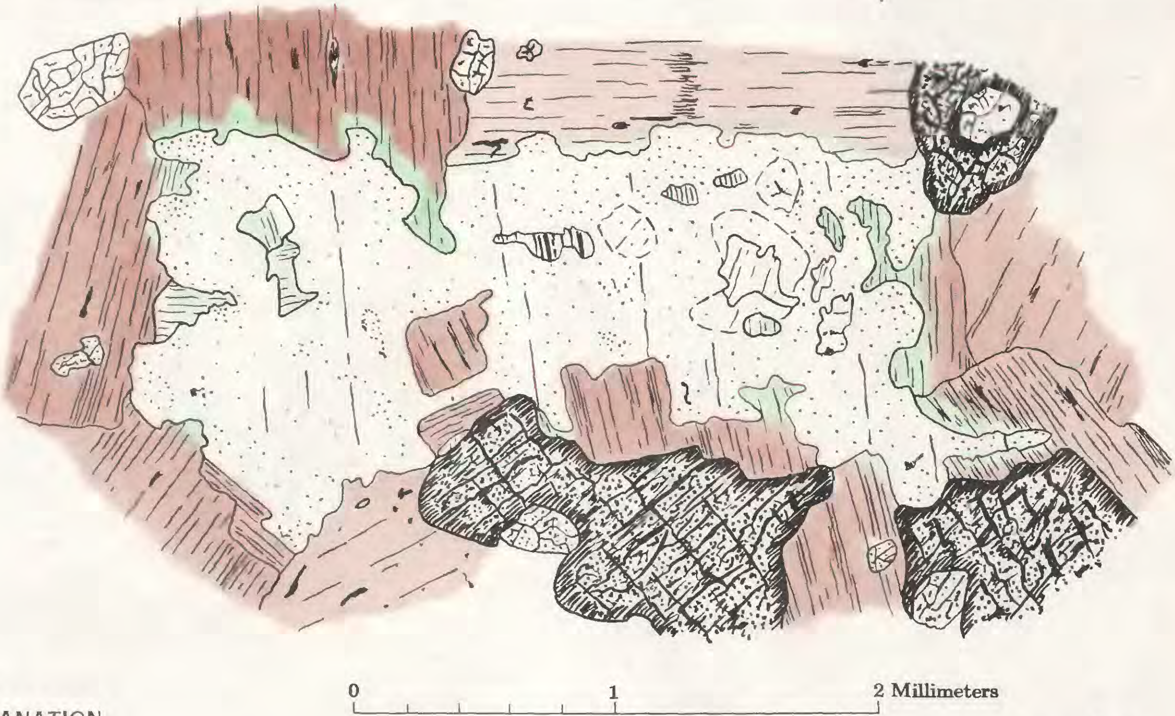
A vague foliation, due chiefly to the orientation of biotite flakes, is found locally in the shonkinite, as indicated by symbols on plate 4, but nearly all the shonkinite appears to be practically devoid of planar structure. The lack of such structure contrasts markedly with the well-developed foliation of the enclosing metamorphic rocks.

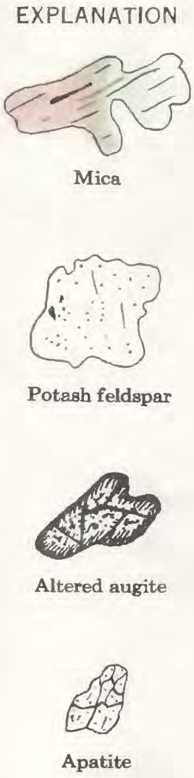
SYENITE

The syenites include feldspar-rich rocks that have less than 50 percent mafic minerals and less than 5 percent quartz. Rocks with 5 to 10 percent quartz are referred to as quartz syenite in this report, and rocks with more than 10 percent quartz are granite. There are all gradations in dark-mineral content, but most of the syenite contains less than 30 percent mafic minerals and some is almost entirely potash feldspar. Typical syenite contains about 80 to 85 percent potash feldspar, 5 percent or less plagioclase, and 10 to 15 percent biotite, amphibole, or more rarely pyroxene. Accessory minerals that occur in variable small amounts are hematite, apatite, sphene, zircon, rutile, and allanite. An orange-brown metamict mineral of mottled appearance, high relief, and low birefringence observed in one thin section is probably thorite.

Much of the syenite is equigranular and relatively coarse-grained (3 to 10 mm). In some porphyritic syenites the orthoclase occurs both as rectangular phenocrysts and in the fine-grained groundmass. The more mafic syenites, with 25 to 50 percent dark minerals, have phenocrysts of biotite, amphibole, or rarely pyroxene, whereas the porphyritic leucosyenite and granite have phenocrysts of potash feldspar. Syenite pegmatite occurs as irregular patches locally in shonkinite and syenite.

Potash feldspar forms the greater part of the syenite and is partly orthoclase, partly microcline, or mixtures of the two; perthitic intergrowths of plagioclase are common. Albite or oligoclase grains typically form 1 to 3 percent, rarely as much as 15 percent, of the syenite, and plagioclase also occurs in the perthite and microperthite. Some perthitic orthoclase crystals are zoned, having strongly sericitized oval cores rimmed by relatively unaltered feldspar.





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INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.

POTASH FELDSPAR REPLACEMENT OF SHONKINITE

Mafic minerals such as hornblende, augite, sodic amphiboles and pyroxenes, and biotite constitute about 10 to 15 percent of typical syenite, but many syenites have virtually no dark minerals. Generally speaking, the darkest rocks contain pyroxene, amphibole, and biotite as mafic constituents, the intermediate mostly biotite and hornblende, and the leucocratic rocks chiefly biotite. Some augite grains have rims of hornblende. Most of the dark minerals are interstitial between coarser grains of potash feldspar, but some are included poikilitically in the feldspar. In other syenites, the mafic minerals are the coarsest grains, and the potash feldspar forms the greater part of the finer-grained matrix.

The soda-amphibole found in some of the syenite occurs partly as medium or coarse grains that probably crystallized relatively early. Crocidolite, the fibrous soda-amphibole, occurs as a relatively late mineral replacing other minerals such as augite, in veinlets cutting other minerals, and in one thin section as fine fibers in quartz radiating from margins toward the centers of quartz blebs that are sparsely distributed in the section. Aegirine-augite occurs in some of the syenite, and some of the soda-amphibole appears to have formed by replacement of this mineral.

In the general mapping of the district (pl. 1), the potash-rich rocks were divided into a unit comprising shonkinite and mafic syenite, and another unit comprising the leucocratic syenite and granite. The complete sequence from shonkinite to granite is divisible into many rock types depending on the degree of detail involved in the study. In addition to the shonkinite and granite, four syenitic rock units, found locally in irregular masses in the larger intrusive bodies, were delineated in the more detailed mapping represented by plate 4 of the Sulphide Queen-Birthday area, and these are described in the following paragraphs.

AUGITE- AND BIOTITE-RICH SYENITE

The augite- and biotite-rich syenite differ from the shonkinite largely in content of mafic constituents. There is a gradual transition between the syenite and shonkinite, and mapping of the augite- and biotite-rich syenite was based upon a mafic mineral content ranging from approximately 25 to 50 percent of the rock. One thin section cut from a dark syenite in a shear zone contains about 65 percent microcline, 15 percent biotite, and 15 percent altered augite. A dark syenitic facies of the coarse-grained syenite at 1770 S., 166 W. of the grid (pl. 4) consists of potash feldspar grains 2 to 3 cm in diameter, poikilitically enclosing mafic constituents which also constitute the material interstitial to the feldspar. The mottled appearance of the rock is illustrated in figure 4. Greenish-brown mica from this rock, with nY and nZ about 1.60–1.61, contains many minute unoriented hexagonal plates of reddish-brown biotite.

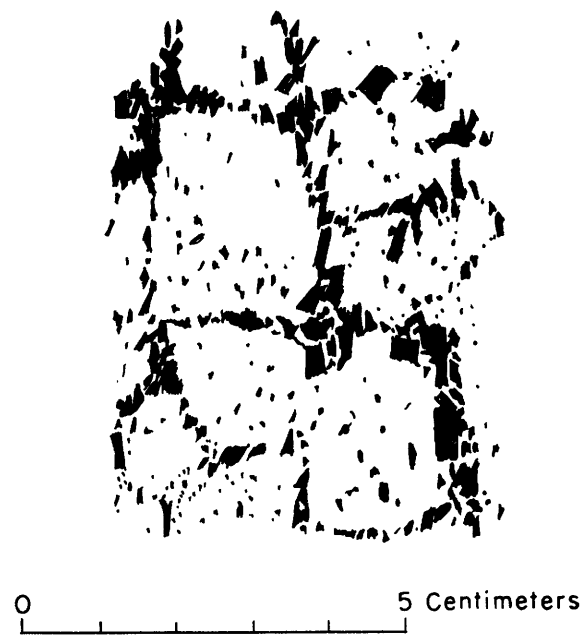


FIGURE 4.—Poikilitic mottled mafic syenite.

COARSE-GRAINED SYENITE

The coarse-grained syenite contains the same minerals as the shonkinite and augite- and biotite-rich syenite but has less than 25 percent dark constituents. The contacts of this syenite with shonkinite are not sharp, but are transitional through a few feet. The texture is like that of the adjacent shonkinite, and is uniform. The grain size is commonly as large as 1 to 2 cm.

FINE-GRAINED SYENITE

The fine-grained syenite grades through quartz syenite to granite, and the quartz content was the only field criterion used to differentiate these rock types. Some individual bodies in the area contain all three types, and contacts between them are both sharply discordant and transitional. Because of this variation, much of the mapping of these rocks was generalized. The grain size of the fine-grained syenite is 1 to 2 mm, but some mafic phenocrysts are as much as several millimeters in length. Minor amounts of biotite, amphibole, and pyroxene constitute the mafic minerals.

Typical of the larger fine-grained syenite bodies is a rock from a dike at the southwest edge of the shonkinite body near the Sulphide Queen mine, east of the map area of plate 4. It consists of 80 percent orthoclase, much of which is perthitic. Many orthoclase crystals contain scattered patches of albite-twinned plagioclase (An_{30}). Biotite and hornblene constitute 8 to 10 percent of the rock, and quartz 2 to 3 percent. Accessory minerals include zircon, sphene, apatite, and opaque minerals.

QUARTZ SYENITE

Rocks similar to the fine-grained syenite in composition and texture, but which contain 5 to 10 percent quartz, have been mapped as a rock unit on plate 4. Although the difficulty of accurately assessing the amounts of quartz in hand specimens is recognized, the distinction has been made to emphasize the gradual transition from syenite to granite. One of the quartz syenite bodies, sampled and examined in thin section, is composed of 75 percent orthoclase, 15 percent albite, 7 percent quartz, and 3 percent hematite and goethite resulting from breakdown of earlier ferromagnesian minerals, and accessory apatite, zircon, and opaque minerals.

GRANITE

Granite in this report applies to those intrusive rocks that contain 10 to as much as 40 percent quartz. Almost invariably the granites are rich in potash feldspar and poor in dark minerals. In color the granitic rocks range from white through shades of gray, pale lavender, or pink, to a dark red on weathered surfaces of the granitic body on Mineral Hill. The thin dikes shown on the map (pl. 1) as undifferentiated granite and leucosyenite are predominantly of granite, but quartz syenites with 5 to 10 percent quartz, and syenites with less than 5 percent quartz, are common, and gradations between them indicate the genetic relationship of these rocks. Modal analyses of two specimens from the Birthday area, given in table 2, indicate considerable variation in composition of the granites. A chemical analysis of a granite from the Sulphide Queen area is given in table 4 (E).

The granites range in grain size from fine to coarse (see pl. 2*B*). Euhedral crystals of pinkish potash feldspar, commonly 2 to 3 mm across and rarely as large as 5 mm, are conspicuous in a matrix of finer grained quartz, potash feldspar, and plagioclase. The potash feldspar crystals are in places broken, and the parts displaced 1 or 2 mm, although no fractures are visible in the enclosing finer grained matrix of quartz and feldspar. Some of the quartz appears to be along subtle parallel streaks; this suggests fracturing or movement during the late crystallization history of the granite. The larger intrusive bodies are generally coarse-grained, whereas most of the thin dikes are fine-grained or porphyritic, with phenocrysts of potash feldspar in a fine-grained groundmass.

The feldspar in the granite is dominantly potassic, as in the syenite and shonkinite. Both microcline and orthoclase are abundant, much is perthitic, and some equant or rectangular grains of potash feldspar are carlsbad-twinned. Micrographic textures are present but uncommon. The potash feldspar in granites in the Birthday area is largely microcline microperthite, in which the perthitic albite locally forms a third or more of the host feldspar crystals. In some of the crystals, the albite blebs are very small, have a common crystallographic orientation, and do not appear to be connected with the edge of the host crystal or to quartz inclusions. These are criteria used by Alling (1933, p. 163) to recognize exsolution blebs. In other host crystals the blebs are more abundant, have shapes and sizes corresponding to the plume or band type of bleb, and appear to be most common adjacent to the borders of the crystals or to quartz inclusions. According to Alling, these characteristics indicate replacement origin.

Grains of albite or oligoclase constitute less than 10 percent of the average granite, rarely as much as 15 percent. The soda content of the analyzed granite (table 4, E) is lower than would be expected from the amount of plagioclase observed in most thin sections of the Mountain Pass granite. The plagioclase is generally clear and unaltered; zoned crystals were not observed. Many of the quartz and plagioclase grains are subhedral to anhedral, and are less than 0.1 mm across; they tend to be clustered together around the much larger crystals of potash feldspar to form a mosaic texture. These small grains also are scattered as inclusions in the coarser potash feldspar crystals. Small quartz inclusions in one microcline crystal in a thin section from the Birthday claims are arranged in a growth zone of the microcline and suggest that at least some of the quartz is contemporaneous with the microcline.

TABLE 2.—*Modal analyses of granite from the Birthday area*

[L. C. Pray, analyst]

	A	*B*
Potash feldspar	66. 5	37. 4
Plagioclase (Ab_{94})	8. 4	24. 4
Quartz	22. 2	37. 6
Other minerals [1]	2. 9	0. 6
	100. 0	100. 0

[1] Includes apatite, sericite, magnetite, and hematite.

The sparse dark minerals that make up less than 5 percent of most of the granite are biotite, hornblende, soda-amphibole (arfvedsonite and riebeckite ?), and rarely pyroxene—essentially the same mafic minerals as in the syenite and shonkinite but in minor quantity. The soda-amphibole and a chloritic alteration product occur locally along fractures in the granite. Accessory minerals include hematite, zircon, apatite, sphene, rutile, monazite, thorite (?), allanite, epidote, fluorite, and leucoxene. Like the other igneous rocks, some granites contain dusty aggregates of iron oxides and carbonate minerals, and probably other fine-grained minerals, within crystal outlines of the earlier dark minerals.

SHONKINITIC DIKE ROCKS

Several shonkinitic dike rocks, similar in composition to the shonkinite in the larger masses, cut the shonkinite, syenite, granite, and metamorphic rocks. The variable mineralogic composition of eight shonkinitic dike rocks is indicated in table 3, and the chemical composition of one sample in table 4. Although these dike rocks are not entirely shonkinitic in the strict sense, they are grouped together because of general similarity of composition and of age relations. The shonkinitic dike rocks had been referred to as lamprophyre (minette) during the field work, but in this report the term "shonkinitic dike rocks" will be used, in order to emphasize the general similarity to the composition of the larger masses.

TABLE 3.—*Mineral composition of shonkinitic dike rocks, Mountain Pass District*

	A	B	C	D	E	F	G	H	I
Feldspars (chiefly potash)	39.0	40.6	55	45	35	15	7	31	61.6
Quartz	2.9	3.1	Tr.	Tr.	--	--	--	--	----
Biotite	29.2	30.0	15	50	20	30	50	35	19.8
Augite and aegirine-augite	19.9	.6	----	----	35	--	30	25	----
Soda-amphibole	5.9	21.4	15	Tr.	--	30	--	--	6.8
Apatite	2.7	2.3	----	2–3	--	5	2	2	4.8
Opaque and iron oxides	.4	----	10	Tr.	--	8	--	--	2.4
Carbonates	----	----	----	Tr.	--	10	10	5	4.6
Other minerals	----	2.0	5	2	10	2	1	2	Tr.

A and B are modal analyses of rocks from Birthday area, by L. C. Pray.
C to H are modal estimates of rocks from area between Sulphide Queen and Birthday areas, by D. R. Shawe.
I, modal analysis of rock from Sulphide Queen area, by H. W. Jaffe.

TABLE 4.—*Chemical analyses of igneous rocks,[1] Mountain Pass district*

[S. M. Berthold and E. A. Nygaard, analysts]

	A Fine shonkinite	B Coarse shonkinite	C Shonkinitic dike	D Coarse syenite	E Granite	F Basalt
SiO_2	47.4	47.9	48.4	57.2	71.4	46.8
Al_2O_3	10.6	11.4	10.6	13.0	13.8	15.8
Total Fe as Fe_2O_3	8.0	7.6	6.4	4.8	1.6	7.8
MgO	10.4	11.4	7.0	4.1	.22	7.6
CaO	8.9	5.4	6.9	2.6	.86	6.9
Na_2O	1.2	1.4	1.3	1.0	.26	3.9
K_2O	7.0	8.2	9.0	11.2	9.6	1.3
TiO_2	1.6	2.2	2.9	.86	.32	1.0
P_2O_5	2.0	1.6	2.4	.58	.03	.16
MnO	.18	.08	.08	.12	.02	.13
BaO	1.2	.63	.83	.98	.26	.05
Ignition [2]	1.1	1.3	3.2	1.5	2.1	9.1
Total	100	100	99	98	100	101
FeO	4.6	4.0	2.7	1.8	0.00	5.0
Fe_2O_3	2.9	3.2	3.4	2.8	1.6	2.3

[1] Spectrographic analyses and locations of these samples are given in table 5.
[2] Includes gain due to oxidation FeO.

TABLE 5.—*Spectrographic analyses for minor elements in igneous and carbonate rocks, Mountain Pass district*

[Chemical analyses of samples A–F are given in table 4. Analyses A–F by Janet D. Fletcher; analyses 26B, 29B, and 32B by Paul R. Barnett]

Sample	Description	Location (pl. 4)	Be	Cu	Pb	Mo	Co	Ni	Ga	Cr	V	Mn	Ge	Sc	Y	Yb	La [1]	Zr	Sr	Ba	P	B	Th
A	Fine-grained shonkinite	2040 S., 708 W.	0.003	0.008	0.02	-----	0.005	0.03	0.002	0.03	0.01	N.d.	-------	0.003	0.02	0.0004	0.08	0.07	0.4	0.7	1.0	-------	-------
B	Coarse-grained shonkinite	Birthday shaft	.003	.005	.01	-----	.004	.03	.002	.06	.02	N.d.	-------	.003	.01	.0003	.03	.04	.4	.6	.8	-------	-------
C	Shonkinitic dike rock	3067 S., 23 W.	.003	.004	-------	-----	.003	.02	.002	.02	.01	N.d.	-------	.003	.01	.0004	.05	.1	.4	.7	1.0	-------	-------
D	Coarse-grained syenite	1771 S., 123 W.	.003	.008	.05	0.01	.002	.01	.002	.01	.009	N.d.	-------	.003	.02	.0006	.4	.05	.1	.6	-------	-------	-------
E	Granite	3685 S., 920 E.	.002	.002	.02	-----	-------	.0009	.002	.007	.002	N.d.	-------	.0002	.006	-------	.03	.03	.1	.3	-------	0.02	-------
F	Basalt	(2)	-------	.003	-------	-----	.003	.01	.002	.05	.02	N.d.	-------	.003	.006	.0002	-------	.006	.08	.07	-------	-------	-------
26B	Carbonate rock from Sulphide Queen carbonate body.	(3)	-------	.00X	.X	-----	.000X	.000X	.000X	.000X	.00X	0.X	0.00X	.00X	.0X	N.d.	X.	.00X	XX.0	XX.0	N.d.	Tr.	0.0X
29B	do	(3)	-------	.00X	.0X	-----	-------	.000X	-------	.00X	.00X	.X	-------	.00X	.00X	N.d.	X.	.00X	.X	XX.0	N.d.	Tr.	-------
32B	do	(3)	-------	.00X	.0X	-----	-------	-------	-------	.000X	.00X	.X	-------	.00X	.0X	N.d.	X.	.00X	X.0	X.0	N.d.	Tr.	-------

[1] Cerium and other elements of the lanthanum group are also present.
[2] Center of 3-foot dike 800 S., 265 E. on map grid of Ray-Welch-Willmore prospects, plate 13.
[3] Location shown on plate 8.

Note:
Looked for but not found (samples A–F):
Ag, Au, As, Sb, Bi, Hg, Rh, Pd, Ir, Pt, W, Re, Ge, Sn, Se, Te, Zn, Cd, Tl, Th, Nb, Ta, U.
Looked for but not found (samples 26B, 29B, 32B):
Be, Sn, Mo, Zn, In, As, Sb, Bi, Cd, Tl, Au, Ag, Pt, U, Nb, Ta, W, Li.

The field evidence indicates the shonkinitic dike rocks are younger than the granite and syenite, for they cut across dikes of these other rocks. Because both the shonkinitic dike rocks and the shonkinite in the larger masses are of unusual composition, the similarity of composition suggests that they are related. Thus the granite must also be a product of the same general period of igneous activity. The shonkinitic dike rocks are cut by carbonate veins in several places. At one point in the Birthday area, a thin dike of fine-grained shonkinite appears to cut across a thin carbonate vein similar to adjacent rare-earth-bearing veins. Although the exposures are not adequate to furnish conclusive proof, the relationships suggest a possible overlap in the time of formation of the shonkinitic dike rocks and carbonate veins.

The shonkinitic dike rocks are composed largely of orthoclase and microcline, biotite, pyroxene, amphibole, and accessory minerals (see pl. 2C). The typical shonkinitic dike rock contains about 30 to 50 percent feldspar, which occurs chiefly as anhedral grains 0.5 to 1 mm in diameter in the groundmass. Most of the feldspar is orthoclase. The plagioclase has a composition of about Ab_{90}. Some of this is untwinned, and is similar in appearance to the orthoclase. Because of the difficulty in distinguishing between these two types of feldspar they are grouped together in the modal analyses of the rock (table 3). The chemical analysis of one of the shonkinitic dike rocks indicates a low soda content (1.3 percent), thus the amount of plagioclase must be correspondingly low, and but a small proportion of the total feldspar.

Light-brown to reddish to pale yellowish-brown biotite is the dominant mafic mineral. The biotite occurs in minute flakes in the groundmass and as phenocrysts as much as 3 mm in diameter. The dark mica ranges from biotite to phlogopite; some of the biotite has an intermediate index about 1.620, whereas other samples of dark mica have indices at least as low as 1.58, in the phlogopite range. The dark mica in two of the thin sections was determined to have a 2V of about 15°, with strong dispersion; this mica is thought to be phlogopitic, and the strong dispersion may be accountable to sodium or manganese.

The pyroxene corresponds in optical properties to augite and aegirine-augite. It occurs as fine grains in the groundmass and as phenocrysts as large as 3 mm. Both large and small crystals of augite are in places rimmed by a narrow selvage of bright green aegirine-augite. Some of the augite crystals show coarse polysynthetic twinning, which has been interpreted by Poldervaart and Hess (1951, p. 483–485) to be indicative of slow cooling of a basic magma. Some phenocrysts of augite show one or two zones of dusty inclusions close to their edges. In much of the rock, the pyroxene crystals have altered to amphibole having optical properties that indicate a range from common hornblende to sodic hornblende. Aggregates of epidote, calcite, and biotite probably represent former grains of augite.

The amphibole occurs as a felt of randomly oriented needles in the groundmass and as phenocrysts several millimeters in length; some amphibole fibers are arranged radially as though replacing an earlier mineral. The amphibole needles are generally unfractured and show crystal terminations.

Quartz makes up generally less than 1 percent of the shonkinitic dike rocks and occurs in irregular anhedral blebs. Apatite and sphene in amount of 1 or 2 percent are relatively abundant accessory minerals. Some apatite grains have embayed corroded edges, except where euhedral grains are enclosed in biotite crystals. The sphene, like that typical of other rocks in the area, is commonly spindle shaped, yellow and pleochroic, with submicroscopic inclusions obscuring the birefringence and imparting a higher apparent refractive index to the minute grains. Other accessory minerals are magnetite, hematite, calcite, and fluorite. Prismatic needles of rutile occur sparsely; most are oriented along crystallographic directions in the biotite.

Two of the thin sections examined show circular areas less than a millimeter in diameter that contain fibrous amphibole prisms radiating inward from the edge toward a quartz-filled center. These probably indicate late development of soda amphibole in voids, with subsequent filling by quartz. In hand specimens of this rock, brownish spherical grains about half a centimeter across are abundant. In thin section these are seen to be feldspars crowded with dusty hematite.

Much of the shonkinitic dike rock is similar in texture to the shonkinite in the larger intrusive bodies but in general is finer grained, averaging about 0.1 to 0.2 mm in grain size. Unlike the granite and syenite dikes the shonkinitic dikes in many places show well-developed flow banding parallel to walls, especially near the contacts. This is evident in hand specimens as a parallel alinement of biotite flakes, and in some thin sections as a like orientation of the pyroxene and amphibole prisms. Biotite-rich dikes show foliation better than biotite-poor types. The contacts of the shonkinitic dikes with syenite, granite, or earlier shonkinite are sharp. The outer borders of the dikes are markedly finer grained than the interior parts; this suggests that the borders are chilled zones.

Several of the shonkinitic dike rocks contain inclusions of older rock. One late shonkinitic dike 20 feet thick, cutting older shonkinite 350 feet S. 60° E. of the Birthday shaft, contains many parallel rounded or slablike inclusions of pre-Cambrian gneiss, commonly about the size of a hand. Contacts between dike rock and inclusions are sharp. The inclusions are oriented parallel to the walls of the dike, and the foliation within the inclusion not uncommonly makes a sharp angle with the long dimension of the slab. The inclusions of gneiss, the sharp outer contacts of the dikes, and the primary foliation indicate that the late shonkinitic dikes were injected along fractures.

The shonkinitic dike rocks that are discordant to the large shonkinite-syenite masses are known to be younger than the larger intrusive masses. The shonkinitic dike rocks in gneiss some distance from the larger masses are probably to be correlated partly with the shonkinite-syenite stocks and partly with the later dikes. Some of the dikes in gneiss have features that suggest the larger intrusive masses, such as coarse grain size, the virtual absence of flow structure or foliation, local compositional variants such as syenitic portions, and absence of quartz. Others resemble the later fine-grained shonkinitic dikes in having fine grain size, or porphyritic texture with phenocrysts of the dark minerals in a fine-grained groundmass, flow structure locally, minor amounts of quartz, small slablike inclusions of gneiss with sharp contacts, general uniformity of composition and texture throughout the dike, and local finer grained chilled margins.

BIOTITE-RICH DIKES NORTH OF SULPHIDE QUEEN MINE

Several thin dikes in an area about 1,300 feet north of the Sulphide Queen mine are rich in biotite and have feldspar content different from that of the shonkinite. Like the shonkinitic dike rocks just described, these biotite-rich dikes cut across and include fragments of granite. The composition of the biotite-rich rock is indicated in columns G and H of table 3. Very likely other dikes of similar composition occur in other parts of the district but have not been distinguished from the other shonkinite dikes because of insufficient petrographic data and similar appearance in the field.

The biotite-rich dikes have fine-grained (0.1 mm) chilled edges, in which the biotite flakes parallel the contacts, and a coarse-grained central part in which the crystals average 1 mm across, but with some biotite phenocrysts as much as 1 cm across. The coarse-grained rock of one dike is composed of about 50 percent biotite, 30 percent aegirine, and 7 percent feldspar, largely twinned albite (An_2) but in part probably untwinned orthoclase. Carbonate mineral makes up 10 percent of the rock, as anhedral grains which enclose minute euhedra of other minerals such as biotite and aegirine, and which are commonly surrounded by fine-grained mosaic biotite. About 2 percent apatite and minor amounts of hematite and opaque minerals are present. The biotite is pale orange-brown and almost uniaxial. Aegirine occurs as relatively small, euhedral, length-fast prisms 0.1 to 0.5 mm long. The aegirine is biaxial (−), 2V about 60°, has approximately parallel extinction and a birefringence about .045, and is pleochroic from green to yellowish-green. The aegirine is locally altered to pale-green fibrous and prismatic amphibole with anomalous interference colors suggesting soda content. Some fibrous chlorite occurs with the amphibole.

The fine-grained edge of the dike has the same minerals as the coarse facies, but in different proportions. Biotite, which constitutes about 35 percent of the thin section from the fine-grained edge, occurs partly in crystals of the same size as those in the central part, but a much higher proportion of the biotite is fine-grained (about 0.1 mm). These small biotite flakes are also flow-alined. About 25 percent of the section is very fine-grained aegirine averaging about 0.05 mm in length. Twinned albite constitutes 21 percent, and orthoclase 10 percent of the section. The subhedral to anhedral feldspars range from very fine-grained to 0.5 mm in size. The 5 percent carbonate is similar in occurrence to that in the coarse facies, but it is finer grained. About 2 percent apatite and minor amounts of opaque minerals and hematite are present. Some of the phenocrysts of biotite are altered to a fine-grained mosaic of biotite around carbonate cores.

Certain of the features described above indicate that there was a relative increase in biotite and aegirine in the center after solidification of the borders. Possibly much of the feldspathic liquid flowed out of an already stabilized mesh of biotite and aegirine, or there was crystal settling in the cooling dike after solidification of the selvages to account for the compositional variation.

The syenite wall rock adjacent to the biotite-rich dike described above is enriched in soda, containing about 65 percent albite (An_{0-2}), 13 percent orthoclase, 10 percent aegirine, 10 percent carbonate mineral, and minor amounts of apatite, opaque minerals, and zircon. The aegirine is replaced but slightly by soda amphibole. The aegirine is concentrated in fissures extending obliquely from the dike, but the soda pyroxene of the syenite is coarser grained than that of the dike.

The 5 to 10 percent of calcite in the biotite-rich dikes suggests that CO_2 may have been abundant when the rock formed. The aegirine in the dikes and the predominant albite in the syenite adjacent to the dikes indicate an excess of soda in these rocks. This may be related to the CO_2 environment and its possible effect upon soda-potash stability relationships.

CONTACTS

The contacts between the potash-rich igneous rocks and their wall rocks are partly fault contacts, partly sharp discordant intrusive contacts, and some show a gradation between gneiss and the potash-rich igneous rocks. Apophyses from the intrusive masses are rare but present in a few places.

Local contact metamorphism, restricted to pre-Cambrian gneisses near the potash-rich igneous rocks and carbonate rocks, is mentioned in the descriptions of the seven shonkinite-syenite-granite stocks (p. 19–25). These contact alterations have not been studied in detail petrographically, but certain features have been noted that suggest the local development of contact rocks similar to the fenite of Brögger (see Brögger, 1920; Von Eckermann, 1948; Adamson, 1944; Dixey, Smith, and Bisset, 1937; and others listed in the bibliography).

Locally near the contacts of the Mountain Pass intrusive bodies the quartz of the gneiss is redistributed, converting some gneisses to quartz-poor syenitic rocks, or recrystallized, forming small blebs, veinlets, and irregular pods of quartz, commonly without wavy extinction. The rocks are locally reddened by disseminated hematite and iron staining along fractures. Microcline grains have formed along foliation planes in the gneiss, thus tending to obliterate the foliation. Microcline perthite grains locally in both the shonkinite and adjoining gneiss are zoned, the cores contrasting in color with the edges. Albite and quartz replace some microcline, particularly near the margins of grains, forming myrmekite. Fresh unaltered grains of well-twinned albite are found among altered and sericitized potash feldspar grains, and biotite, soda-amphibole, and sodic pyroxene have been introduced or recrystallized in some of the contact rocks. Crocidolite has formed along seams or veinlets in both intrusive and adjacent wall rocks.

The large shonkinite-syenite mass in the Birthday area contains partially assimilated gneissic rocks locally in a zone several feet wide near the border. This zone consists largely of shonkinite that is finer grained and appears less mafic than the average rock in the intrusive mass. Near the contact are zoned crystals of potash feldspar, whose light-gray or pink cores suggest feldspar from the gneiss. The rims, 1 to 2 mm thick, are the characteristic grayish-red of the potash feldspar in the shonkinite. The cores are locally embayed and filled with the darker feldspar. The feldspar crystals showing overgrowths do not appear to be systematically oriented within the rock of the contact zone, even though they are abundant and some occur within an inch or less of the augen gneiss. The contact between the augen gneiss and the shonkinitic rock containing the gneissic inclusions and feldspar overgrowths is sharp. These relationships suggest intrusion of shonkinitic magma, and partial assimilation of the host rock locally along its contact with the shonkinite.

Breccia composed of feldspathized pre-Cambrian gneiss blocks in granite or syenite is conspicuous along the east side of the Mineral Hill granite body. Fragments of pre-Cambrian gneiss in the breccia diminish in size and number toward the inner part of the Mineral Hill intrusive body, which is almost entirely granite and syenite. Similar breccias, the fragments and matrix of which consist of granite, syenite, and shonkinite, in addition to gneiss, are found at many of the contacts of the gneiss with the Sulphide Queen shonkinite-syenite mass. These breccias undoubtedly formed at the time of emplacement of the granite, syenite, or shonkinite.

ALTERATION

The potash-rich rocks in much of the area are slightly altered. Some late magmatic or deuteric effects are indicated by local alteration of pyroxene to hornblende or soda-amphibole, amphibole and biotite to chlorite, and augite to aegirine-augite. Small grains of fluorite of late magmatic or postmagmatic origin are not uncommon as a minor constituent of the granite and late shonkinitic dikes. Aggregates of riebeckite, fluorite, iron oxides, biotite, and chlorite in one thin section of granite appear pseudomorphous after pyroxene grains.

Locally, the potash-rich rocks are extensively altered, especially along shear zones and near carbonate veins. The alteration consists of replacement of feldspar and mafic minerals by calcite, dolomite, or ankerite in irregular patches; veinlets of carbonate and quartz, with minor barite; yellowish- or reddish-brown goethite and hematite along fractures; sericitization of potash feldspar; bleaching of the biotite or oxidation of it to a reddish-brown color, associated with opaque yellow veinlets and dark spots of iron oxide; and local introduction of pyrite. Chlorite and aggregates of chlorite, calcite, epidote, and iron oxide are pseudomorphous after biotite, pyroxene, or amphibole grains. Serpentine has been found in some of the altered shonkinite. Gypsum was noted in a thin veinlet in a fracture in shonkinitic dike rock underground in the Sulphide Queen gold mine.

The granite and syenite are less altered than the darker shonkinite and gneiss, but the leucocratic rocks are commonly reddened near shear zones. Thin section examination reveals the development of carbonate and other fine-grained minerals, including iron oxides, in the sparse augite, and of iron-stained carbonate and quartz in the closely spaced shears. Some quartz in the shear zones is strained and shows cataclastic features.

The late shonkinite dikes are also altered where cut by shear zones. A thin section typical of the altered shonkinite dike in the shear zone at 3058 S., 494 W. of the grid (pl. 4) is composed of phenocrysts of pale yellowish-brown phlogopite, rimmed by a selvage of quartz, in a fine-grained matrix that is largely potash feldspar, phlogopite, irregular blebs of apatite, and minor sphene. Iron oxide occurs along seams, as dust throughout the section, and as pseudomorphs of minute needles in the groundmass. Also scattered through the section are minute irregular blebs of a pale yellow-green to greenish-brown platy mineral, possibly nontronite, with refractive indices of about 1.6, birefringence between .03 and .04, uniaxial or with a small 2V, and negative. Seams in the rock are filled with muscovite, probably iron-rich as suggested by a 2V of about 20°, birefringence .035, and refractive indices of about 1.6.

Dark green chlorite-rich dikes occur in several areas of gneiss near the Clark Mountain fault (pl. 1), and probably are altered shonkinite. They are older than the faulting and are locally cut by closely spaced shear planes that parallel the Clark Mountain fault. In three thin sections of these green rocks, orthoclase or microcline microperthite or both range from 0 to 35 percent; chlorite 30 to 50 percent, apparently pseudomorphous after biotite and amphibole; carbonate is nearly 10 percent of one section and 30 to 40 percent of the others, occurring as an alteration product of mafic minerals, in veinlets, and apparently replacing feldspar grains; quartz is present in amounts from nearly 0 to 15 percent; and there are minor quantities of iron oxides, apatite, sphene, epidote, and allanite.

PRINCIPAL STOCKS AND INTRUSIVE BODIES

SHONKINITE-SYENITE BODY NEAR SULPHIDE QUEEN MINE

The largest of the potash-rich intrusive bodies in the district, the composite shonkinite-syenite stock north of the Sulphide Queen mine, is shown in plate 1, and the southwestern part of it in plate 4. The stock is about 6,300 feet long and 1,800 feet in maximum width. The long dimension of this body is N. 65° W., and it cuts across the general trend of the pre-Cambrian foliation which is variable near it but averages about N. 20° W. The irregular intrusive contacts of the stock dip southwestward at angles of 25° to 70°, but in several places the contact is formed by steeply dipping faults trending about N. 60°–70° W. An exposure of shonkinite in the pre-Cambrian rocks just north of the large carbonate mass shows the attitude of the shonkinite-gneiss contact, which here strikes N. 20° W. and dips 25° SW.

The stock is composed chiefly of shonkinite which grades into irregular, small, erratically distributed masses of augite, hornblende, or biotite syenite, or pink syenite composed of 80 percent or more pink to grayish-red microcline, some biotite, and a little amphibole or pyroxene. These local variants are not indicated on plate 1, the geologic map of the district. Quartz is largely absent from the syenite, and where observed it occurs as a minor mineral in small patches with coarse-grained microcline. Many contacts between shonkinite and syenite are gradational, but some are sharp. Locally, small shonkinite fragments are enclosed in syenitic matrix.

The distribution of the principal rock types in part of the intrusive body is shown in plate 4, in which the intrusive rocks have been divided into shonkinite, augite- and biotite-rich syenite, coarse-grained syenite, fine-grained syenite, quartz syenite, granite, and late shonkinitic dikes. For the most part the irregular syenite patches grade into the shonkinite, but the quartz syenite, granite, and late shonkinitic dikes typically cut the shonkinite-syenite complex with relatively sharp contacts.

The granite generally forms conspicuous, light-brown, resistant outcrops within the shonkinite area. Most of the dikes are a few feet or a few inches thick, but a few of the granite dikes are more than 100 feet wide. They are nearly vertical; most strike northwest to west and dip steeply south or southwest. The largest and most abundant dike rocks cutting the shonkinite-syenite mass are granite and fine-grained pink syenite. At least two types of granite are recognizable in the field. A granite with white potash feldspar constitutes some of the dikes that cut a pink feldspar granite similar in aspect to the pink syenites. Examples of light granite cutting pink granite occur at 2045 S., 500 W., and at 2550 S., 350 E. of the map grid (pl. 4). The granite in places grades into quartz syenite and syenite.

A quartz syenite about 1,000 feet east of the Sulphide Queen shaft contains about 20 percent dark minerals which are biotite, hornblende, and augite, and 5 to 10 percent quartz. Recrystallization and replacement are indicated by several features of the rock. An unzoned phenocryst of andesine 3 mm in diameter is rimmed with a narrow border of orthoclase. Several perthitic orthoclase crystals have oval cores, partially altered to sericite, whose optic orientations differ from those of the rims. Development of perthite is greatest at the edges of orthoclase crystals. The augite of the rock constitutes the cores of many hornblende crystals. Fine-grained aggregates of opaque minerals and brown and green biotite, and aggregates of minute interlocking feldspars peppered with biotite and opaque minerals, occur within crystal outlines of earlier minerals.

About 15 late shonkinite dikes have been shown on plate 4. The faulted segments of one dike total more than 2,000 feet in length. This dike is 10 to 30 feet wide, strikes N. 60° E., and dips 70°–80° S. The dark fine-grained shonkinite dikes cut the granite dikes in several places and commonly have fine-grained chilled margins, indicating their relatively late age. Some of the dikes that are only a foot or two thick are essentially continuous over lengths as much as 400 feet. The smaller shonkinitic dikes are parallel to many of the carbonate veins and the granite dikes. Inclusions of gneiss, 1 or 2 inches across, are common but form less than 1 percent of the shonkinitic dikes.

The granite and late shonkinite dikes, as well as the carbonate veins, appear to have been emplaced in fractures in the shonkinite-syenite mass and adjacent gneiss. This is shown by the parallelism of dikes in certain areas, sharp angular intersections of segments, generally fine grain size, and sharp dike contacts that locally have relatively fine-grained chilled margins. Between the Birthday and Sulphide Queen areas the dikes generally form a conjugate system, the sets of which strike roughly northwest and northeast, in both the metamorphic rocks and the shonkinite. The northeast-trending dikes are generally vertical. Syenite and granite bodies in the area of plate 4 are cut by dikes of light-colored granite, trending northwest and northeast, suggesting that the forces controlling the structure were persistent through the period of igneous activity. A foliation, manifested by parallel biotite flakes, is found in a few places in the shonkinite-syenite mass; it strikes about N. 75° E. and dips steeply south, corresponding in attitude roughly with the northeast set of dikes in the area. Foliation is found, although rarely, along unoriented shears in the shonkinite. In general, however, there is a notable lack of foliation in the shonkinite-syenite mass.

The shonkinite in many areas, for instance in the vicinity of 2150 S., 125 E. in the grid system (pl. 4), is a breccia of mafic fragments in lighter material, cut by a ramifying web of granitic and syenitic dikes. The granite in places contains rounded, reaction-rimmed inclusions of older light to mafic syenite, indicating that the granite probably was fluid at one time. Smaller dikes of granite within the shonkinite body also contain breccia fragments of shonkinite. A few small inclusions of gneiss, 10 to 20 feet in diameter, occur within the shonkinite, but gneiss inclusions are not abundant.

Near the contact about 1,000 feet east of the Sulphide Queen mine, the stock is a complex assemblage of shonkinite, dark biotite or hornblende syenite, pink biotite or hornblende syenite with only minor dark minerals, pink leucosyenite, quartz syenite, and granite. Similar assemblages of rock units, many less than a foot thick and therefore impractical to show at the scale of the district map, are found in other parts of the stock. These small irregular masses show a sequence of intrusion in order of decreasing basicity. In this part of the stock, relatively coarse-grained biotite shonkinite forms the border along most of the contact, and many fragments of it are included in quartz syenite and granite. Inch-thick dikes of lighter-colored syenite cut mafic syenite or shonkinite, and one specimen of porphyritic pink syenite shows a fine-grained chilled margin against shonkinite. The gneiss adjoining this part of the stock locally contains abundant biotite and potash feldspar that appear to have been introduced into, or reconstituted from, the pre-Cambrian gneiss.

The contacts between the intrusive complex and the gneiss are in places sharp; in other places gradational with evidence of replacement of the gneiss by minerals such as soda-amphibole, aegirine-augite, and potash feldspar, characteristic of the shonkinite; and in places the contacts are faults.

Along part of the intrusive contact a breccia zone about 10 feet thick occurs in which fragments of pre-Cambrian gneiss are enclosed in and partly replaced by syenitic or shonkinitic material. In places the gneiss fragments, in which the foliation is still discernible, and the gneissic wall rocks within a few feet of the shonkinite, appear to have been enriched in potash feldspar. Some of the potash feldspar crystals are zoned, having lighter-colored cores and darker pink or purplish rims. Similarly zoned potash feldspar crystals are found locally in shonkinite devoid of foliation. The dark minerals of the gneisses, especially garnet and probably the amphiboles and pyroxenes, are typically altered to aggregates of phlogopitic biotite and magnetite, commonly with feldspar, hematite, and carbonate.

The northern part of the area mapped in detail (pl. 4), east of the Birthday area, includes a segment of the gneiss-shonkinite contact along which is a breccia composed of several of the rock types. Farther south within the shonkinite, at about 1450 S. and between 460 and 670 W. of the map grid (pl. 4), blocks of altered gneiss lie roughly parallel to the strike of the country rock gneiss. The mafic and granitic layers of gneisses, which are as much as 1 cm thick, are altered. The mafic minerals and garnets are replaced by aggregates of dark mica and magnetite. The potash feldspar is dark pink like that of the shonkinite, but some of the dark pink feldspar has cores of white and pale-pink feldspar.

Two specimens of these gneisses were examined in thin section. The first contains microcline with minor orthoclase (in places perthitic), sillimanite, garnet, phlogopitic biotite, quartz, magnetite, and zircon. Sillimanite occurs as large prismatic grains up to several millimeters in length, and as needles in fine-grained green biotite and magnetite. Scattered garnet blebs are surrounded by aggregates of green biotite and magnetite. Reddish-brown biotite flakes are as much as several millimeters in diameter. Rounded grains of zircon, surrounded by pleochroic haloes, are enclosed in biotite. Quartz occurs as scattered grains and in vermicular intergrowths with potash feldspar.

The second specimen is composed of albite, potash feldspar, sillimanite, phlogopitic biotite, spinel, magnetite, quartz, and minor amounts of allanite and zircon. Carbonate occurs in late seams, and as isolated grains with the aspect of primary constituents. Much of the albite is replaced by potash feldspar to form patch perthite. The albite occurs as aggregates of disordered twinned crystals, aggregates of oriented but discrete units (fig. 5), and single crystals 2 or 3 mm in length. This is interpreted to indicate a progressive formation of single albite crystals from disordered units of albite. Sillimanite occurs as single crystals and as aggregates of minute semiparallel prisms surrounded by fine-grained aggregates of potash (?) feldspar, greenish-brown biotite, and spinel (fig. 6). The spinel occurs as minute, bright-green, isotropic octahedra, and is probably a magnesium-iron spinel.

Along the contact southeast of the rocks just described, in the vicinity of 2600 S., 65 E. of the grid

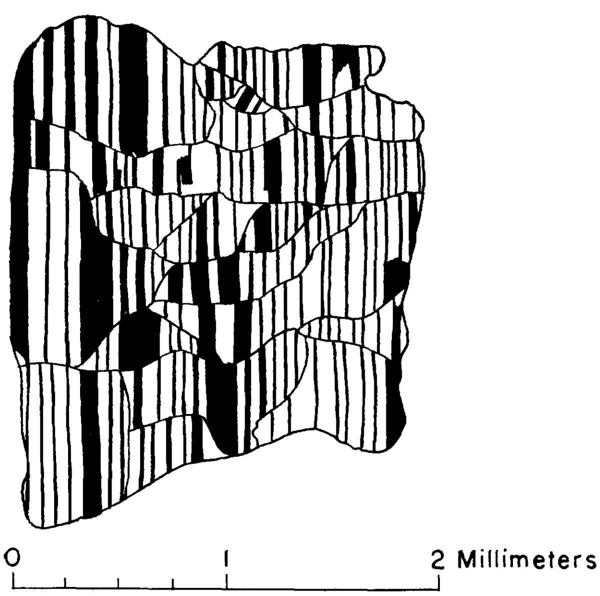


FIGURE 5.—Twinned albite composed of many oriented units.

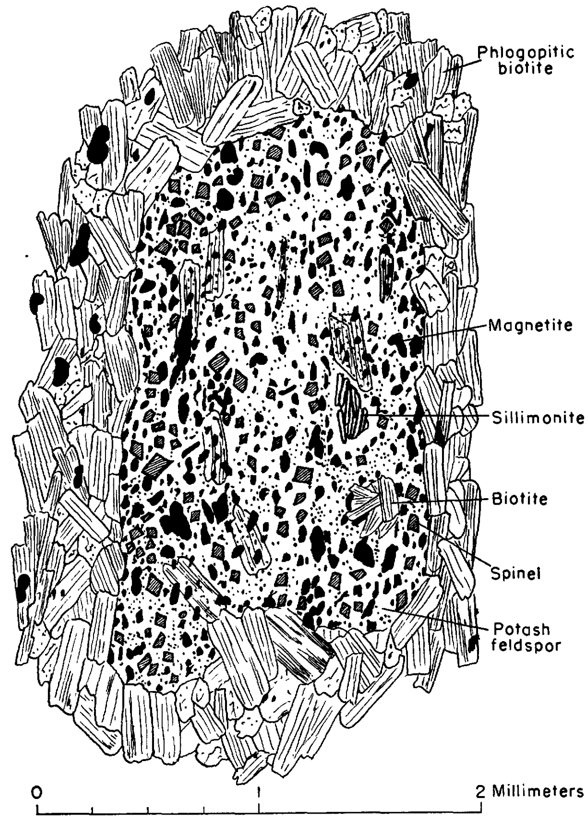


FIGURE 6.—Aggregate of spinel, biotite, and magnetite in potash feldspar groundmass.

system on plate 4, altered gneiss, granite, syenite, and shonkinite are found in a complex contact zone. One specimen from this gneiss-shonkinite contact zone is composed of syenite and shonkinite in alternating layers about 3 to 4 cm thick. A thin section of one of the syenite layers has about 70 percent microcline with minor orthoclase and perthite, some with dusty alteration; 20 percent soda-amphibole; 7 percent euhedral apatite crystals as long as 2 mm; and minor amounts of sphene, zircon, hematite, and opaque minerals. The soda-amphibole adjacent to apatite has optical properties that differ from those of soda-amphibole in other parts of the same grain, and is, therefore, thought to have been enriched in soda. Similar relations between soda-amphibole and enclosed apatite, found in a thin section of shonkinite from the large intrusive mass north of the Sulphide Queen mine, are illustrated in figure 7. In this, the greater part of the amphibole is biaxial (−), 2V 65° to 70°, with very strong dispersion, $v>r$. The pleochroic scheme is X pale-yellow, Y violet-brown, Z pale greenish-brown; absorption $Y>Z=X$. Pleochroism of the apparently more soda-rich variety is X, yellowish (?); Y, sky blue; Z, violet; dispersion is extreme, $v>r$. The apparent enrichment

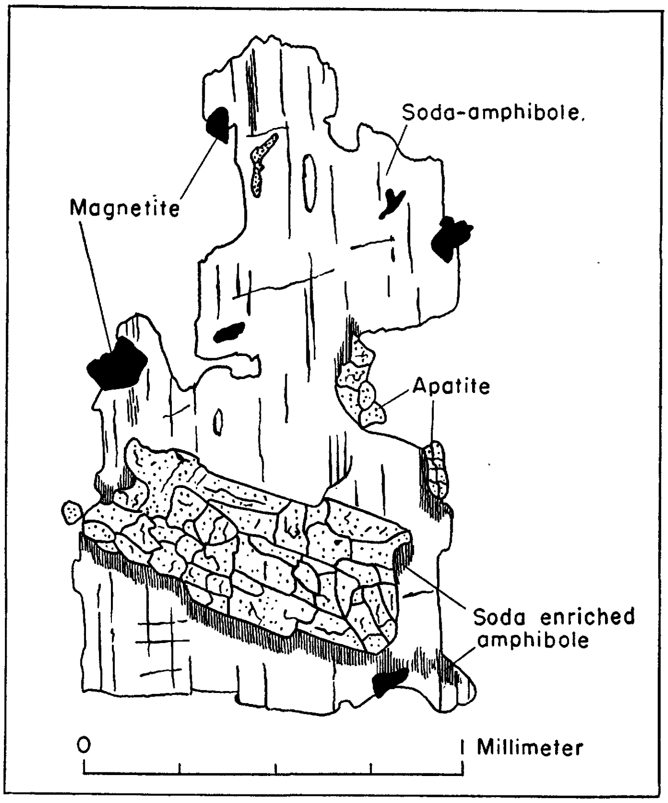


FIGURE 7.—Development of soda-enriched amphibole adjacent to apatite.

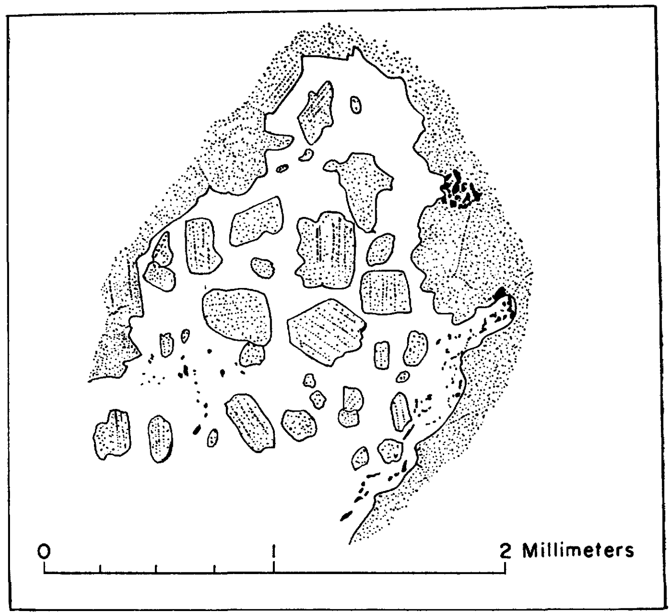


FIGURE 8.—Clear potash feldspar replacement of gneiss. Dusty plagioclase is locally embayed by potash feldspar having uniform orientation.

in soda was probably directional in nature, for it occurs only on certain sides of the apatite grains.

The altered gneiss near the syenite-gneiss contact, 100 feet north of the rock described above, shows patches as much as 5 mm in diameter composed of fine-grained dark mica and opaque minerals, in part hematite, derived through alteration of garnet porphyroblasts, in a feldspathic groundmass. A thin section of the rock shows dusty altered plagioclase and clear plagioclase, orthoclase with albite as patch perthite, green and brown biotite developed in different areas as fine-grained aggregates, soda amphibole, some quartz, magnetite and hematite, and minor amounts of zircon, fluorite, and a carbonate mineral. Clear plagioclase and potash feldspar occur along linear zones which may represent recrystallized portions. Clear potash feldspar replaces parts of the rock, leaving some dusty plagioclase as relict embayed crystals (fig. 8).

SHONKINITE-SYENITE BODIES NORTHEAST OF GROVER SPRING

About 3,000 feet northeast of Grover Spring are two composite shonkinite-syenite bodies separated by about 400 feet of gneiss. Both intrusive bodies are elongate in a northwesterly direction and appear to dip about 45°–60° SW. The southeastern body is about 1,750 feet long and 200 to 450 feet wide, and the northwestern is about 1,250 feet long and 150 to 350 feet wide. Their similarity in composition and structure suggests that they may be parts of the same mass connected at depth. Many thin dikes of granite and a few of syenite and shonkinite are concentrated in the gneiss just west of these bodies and generally parallel the foliation.

The general distribution of the principal rock types making up these two shonkinite-syenite bodies is shown in plate 1. The biotite shonkinite is composed generally of 50 percent or more biotite and pyroxene, about 5 percent fibrous blue soda-amphibole, and the rest largely pink to purplish orthoclase. This rock ranges from fine- to coarse-grained, and is somewhat finer grained on the average than the lighter colored syenites in this body. Irregular masses of the biotite shonkinite occur near the margins of the intrusive bodies, as shown on the map, and small masses too thin to show at this scale form a discontinuous border at many places along the contacts with gneiss. Locally the grain size diminishes within a few inches of the contact. The shonkinite is cut by thin dikes and irregular pegmatitic patches of lighter colored syenite, and a few inclusions of the shonkinite occur in syenite of the main body and syenite dikes nearby, demonstrating the shonkinite to be the oldest rock in the composite intrusive bodies.

Much of the southern half of the southeastern body is a mafic syenite, slightly more felsic than the shonkinite. The mafic syenite contains on the average 25 percent blue amphibole and clinopyroxene, 5 to 20 percent biotite, and the remainder largely potash feldspar.

The grain size is medium to coarse, but locally becomes somewhat finer within a foot of the contact with the shonkinite.

The greater part of the two intrusive bodies northeast of Grover Spring is composed of syenite containing less than 5 percent biotite on the average, about 5 to 15 percent blue amphibole and clinopyroxene, and the remainder pink, orange-red, or flesh-colored potash feldspar. The rock is almost invariably a shade of red because of the high potash feldspar content and abundant hematite stains. Contacts between the syenite and the mafic syenite or shonkinite are commonly sharp, and the grain size of the syenite appears to diminish slightly within a few inches of the contact. Inclusions of shonkinite occur sparsely in the syenite, chiefly near the margins. They are somewhat altered and contain spotty coarse crystals of potash feldspar that appear to have replaced part of the inclusions. Dark minerals in the syenite are slightly more abundant within a few feet of the north and east margins, and locally near the inclusions of shonkinite, than elsewhere. A few thin dikes of syenite cut shonkinite. These contact relations and the inclusions of older syenitic rock in younger suggest that the syenite, mafic syenite, and shonkinite are separate though closely related injections.

Several thin dark dikes appear to cut the syenite. One of these, about 2 inches thick, is rich in biotite, darker than the syenite, but more felsic than typical shonkinite. Another dark dikelike body of shonkinitic composition, about a foot thick, contains fine- to medium-grained biotite, aegirine, and soda-amphibole, in a fine-grained feldspar groundmass. The dikelike body is discontinuous and at several places is breached by the surrounding aegirine-amphibole syenite. The contact between the dike and the syenite is marked by pegmatite, less than an inch thick, composed of potash feldspar, aegirine, and quartz.

Small patches of syenite pegmatite are common near the margins of these composite bodies. The pegmatite consists largely of potash feldspar with both fibrous and coarsely crystalline blue amphibole, aegirine, and very little biotite. A few small vugs lined with quartz, or of quartz and minor specularite, are found in peripheral parts of the syenite and in the adjoining gneiss. The foliation of the gneiss is deformed locally near the intrusive bodies.

At the south end of the southeastern body, the granitic augen gneiss within 100 feet of the contact is cut by many small dikes of syenite or granite. Near these dikes, the pre-Cambrian gneiss is partly replaced by syenitic material, and potash feldspar grains have developed in the gneiss. Some of the syenite near this contact is composed of 50 to 85 percent microcline and microcline perthite, which occur in subangular grains that are partly light- and partly dark-gray in hand specimen. As seen in thin section, the dark portion, which forms a border around a relatively clear core, is potash feldspar with the same optical orientation but crowded with many dusty opaque particles, probably hematite. Coarse grains of this microcline, constituting 65 to 85 percent of four thin sections of these rocks, are separated by interstitial quartz with minor opaque minerals, hematite, amphibole, and biotite. One of the specimens of syenite composition has a gneissic structure. Other minerals that constitute a fraction of a percent to 5 percent of the four thin sections are biotite, arfvedsonite, zircon, opaque minerals, sphene, albite, muscovite, chlorite, allanite, and epidote. Quartz occurs in myrmekite and appears to replace soda-amphibole and other minerals. Some epidote grains have cores of allanite. Sphene is commonly associated with the opaque minerals. The soda-amphibole (arfvedsonite) is pleochroic, with X, light blue; Y, violet; Z, pale greenish-gray.

SHONKINITE-SYENITE BODY SOUTHEAST OF HIGHWAY MAINTENANCE STATION

The composite shonkinite-syenite body about 4,000 feet southeast of the highway maintenance station is about 2,000 feet long, in a N. 45° W. direction, and 300 to 600 feet wide. Biotite shonkinite or dark biotite-rich syenite constitutes roughly half of the body and occurs along its northeast side. Pink to purplish-gray syenite makes up most of the rest of the body, mainly along its southwest side and as small dikes or pods in the shonkinite. The syenite is mostly potash feldspar, with a very few percent of amphibole and pyroxene. Dikes of granite and quartz syenite, containing 5 to 25 percent quartz and very little dark mineral, cut the shonkinite. The shonkinite is altered locally to irregular light-colored patches in which the altered biotite is nearly colorless. Crocidolite and carbonate veinlets 0.1 to 0.3 inch thick are common.

The irregular northeastern contact of the intrusive body appears to dip about 50° SW. on the average. The southwest contact is partly an almost vertical fault and partly an intrusive contact with the pre-Cambrian gneiss, which is dominantly granitic augen gneiss. In places near the syenite and shonkinite the gneiss is impregnated with feldspathic material. In one place near the south contact, pre-Cambrian gneiss is brecciated, and small fragments with gneissic structure, an inch or two in diameter, are enclosed in fine-grained syenitic groundmass. The syenitic material in this breccia is about 80 percent orthoclase, clouded with dusty inclusions and alteration products; about 5 percent each of quartz, actinolite, and opaque minerals; and minor amounts of epidote, biotite, apatite, plagioclase, chlorite, and sericite.

At one place near the northeast contact, the gneissic wall rocks megascopically appear to be impregnated by feldspar and quartz from the intrusive body. Examination of two thin sections indicates that these gneissic rocks consist of 35 to 40 percent quartz, 10 to 20 percent myrmekite, 20 to 40 percent orthoclase, 20 percent albite in one section, and minor amounts of biotite, opaque minerals, chlorite, muscovite, and apatite. The vermicular quartz-feldspar intergrowth, myrmekite, appears to have formed through the partial replacement of orthoclase by albite and by quartz, particularly near the borders of orthoclase grains. Many of the irregular quartz patches that appear to have formed in the rock by replacement are bounded by abundant biotite and opaque minerals.

The wall rocks adjoining the shonkinite-syenite body contain a few blebs or pockets of quartz and specular hematite, similar to those associated with the other intrusive bodies south of U. S. Highway 91.

POTASH-RICH SYENITES NEAR MEXICAN WELL

Two potash-rich leucosyenites occur within half a mile of the Mexican Well, one southwest of it and the other southeast. The intrusive body southeast of the well is about 300 by 400 feet in plan. Near the margins it is coarse-grained red syenite or quartz syenite consisting chiefly of potash feldspar and containing about 5 percent quartz. Near the center of the body the rock is finer grained, and patches contain quartz, partly in euhedral terminated prisms, in amounts as much as 20 percent of the rock.

The potash syenite body southwest of Mexican Well, about 600 by 750 feet in plan, contains 80 to 90 percent potash feldspar on the average and is generally poor in dark minerals. Locally, dark minerals constitute 15 to 20 percent of the rock, mostly as fibrous dark-blue amphibole and dark pyroxene. Quartz is sporadically distributed in amounts generally from 1 to 5 percent, and some of the quartz grains are terminated crystals. Much of the syenite is dark red because of iron staining, and a few small vugs and quartz blebs like those associated with the red granite of Mineral Hill have been observed.

RED GRANITE OF MINERAL HILL

The red granite of Mineral Hill is a composite plug-like body that is partly biotite syenite, partly leucosyenite, and mostly granite. The dark minerals range from almost none to 20 percent of the rock. Biotite is the most abundant dark mineral, but amphibole is also common. The percent of quartz ranges from 40 in quartz-rich granite to almost zero in syenitic parts. Some quartz grains are euhedral crystals. Among the accessory minerals in all the rocks of this mass are magnetite, sphene in amounts of several percent locally, as much as 2 percent specularite, and zircon, allanite, and rare thorite (?).

The granite plug is about 600 by 1,500 feet in plan. The northeast (footwall) contact dips about 65° SW. approximating the dip of the body as a whole. Contacts with the pre-Cambrian gneiss are irregular in detail and are largely discordant to the foliation. The contact relations are complex, and in a zone 200 feet thick along the northeast side the granite contains many inclusions of the pre-Cambrian biotite gneiss, pegmatite, and granitic augen gneiss. Blocks of gneiss 40 feet or so in diameter are generally oriented parallel to the foliation of the gneiss wall rock, but smaller blocks about 3 feet in diameter have random orientation. Contacts are so gradational that in places it is difficult to draw a sharp line between the granite body and gneissic wall rocks or inclusions.

The gradation between unaltered gneiss wall rock and granite is shown first by the appearance of many quartz seams and pods in the gneiss, some reddening of the rock, and iron staining along fractures. Inward toward the granite, patches of red feldspar appear in the gneiss, and as these become larger they are speckled with quartz. The gneissic structure is gradually obliterated by the penetration of feldspathic material along foliation planes and the increase in number and size of the red feldspar patches. In this replacement by potash feldspar, the foliation of the biotite-poor granitic augen gneiss is lost more readily than that of biotite gneiss, because the oriented biotite flakes persist in some of the altered rock. In a more advanced stage, larger dike-like bodies of the granitic material separate blocks of gneiss. The proportion of granite increases inward, until it predominates over the small inclusions in which commonly feldspar has been introduced, the quartz redistributed, and the dark minerals altered. Centrally from the 200-foot zone of mixed rock the inclusions are fewer, and they are practically absent in much of the granite.

Not all of the borders of this granite mass are so complex structurally as the mixed rock described in the preceding paragraph. Some contacts are sharp and straight even though discordant to the foliation, uncomplicated by inclusions or apophyses, with only minor contact effects, such as iron staining and small quartz veins and vugs in the gneiss.

Within the intrusive body, a sequence of formation of the syenitic and granitic rocks is indicated by inclusions of one in another and by more siliceous dikes cutting less siliceous rock. Irregularly shaped quartz-poor inclusions, commonly 10 to 15 feet in diameter, of biotite syenite and quartz syenite, grade almost imperceptibly into the surrounding granite, through increasing quartz and decreasing biotite and hornblende content. As in other parts of the district, the general order of rock crystallization is from less siliceous to more siliceous. For example, pink biotite or hornblende syenite includes fragments of pre-Cambrian gneiss and is in turn enclosed in granite, into which it grades by changing proportions of quartz and potash feldspar. These rocks in turn are cut by fine-grained, quartz-rich granite dikes a few inches thick, with sharp contacts.

Many thin, chiefly granitic dikes occur in the gneiss surrounding the red granite. Some of these are apophyses of the main mass, but others cut both the granite and the gneiss. Commonly near the main mass many thin branching dikes occur in weblike arrangement.

Quartz veins, rarely as much as 2 feet thick, cut the granite and adjoining gneiss. Quartz and specularite occur as blebs and line drusy cavities, commonly 1 to 8 inches in diameter, in the granite near its margins and, to a lesser extent, in the gneiss. Quartz makes up the greater part of these cavity-fillings, and generally occurs on their walls, coated with later specularite. Some of the cavities contain a dull black substance, light brown in powder, much of which is probably siderite. Apparently after consolidation of the granite, solutions corroded it and the gneiss nearby and deposited quartz and specularite.

Small patches of granitic or quartz syenitic pegmatite, commonly 1 or 2 inches in diameter, occur in the granite, and some pegmatitic streaks several inches thick and several feet long appear to have formed along fractures. In one small area about 40 feet square near the northeast contact the granite is banded. Hornblende-rich bands about an inch thick, with 20 to 40 percent feldspar, alternate with light bands having at least 70 percent feldspar. Both bands contain quartz.

ANDESITE AND RHYOLITE DIKES

The dike rocks that will be referred to herein as andesite, in reference to their average composition, actually include a range in composition from basaltic to rhyolitic. On the geologic map, plate 1, the felsitic rhyolite or quartz latite dikes have been distinguished from the darker intermediate types. The andesitic dikes trend westward in contrast to the northwesterly trend of most of the potash-rich dikes and the pre-Cambrian foliation. They are probably of Tertiary age, like other similar rhyolite, latite, andesite, and basalt dikes in the Ivanpah quadrangle (Hewett, in preparation). They cut across the potash-rich dike rocks, but are older than some of the faulting. The andesitic and felsitic dikes range from about 1 to 20 feet in thickness, and some are more than a mile in length.

The andesitic dikes are commonly dark green or gray, but black, brown, buff, or pinkish shades are also found. Andesine is the chief constituent and commonly makes up about 50 to 60 percent of the rock. It occurs as small lath-shaped phenocrysts about 1 mm long and more abundantly in the aphanitic groundmass. The plagioclase is labradorite in some dikes of basaltic composition. Hornblende commonly makes up about 20 to 40 percent of the andesitic dike rocks, and a little augite occurs in some dikes. Light-brown pleochroic hornblende, with an extinction angle of 20°, occurs both in phenocrysts and groundmass and makes up about 20 percent of one typical thin section. Augite constitutes about 5 percent of another section. Magnetite makes up 1 to 5 percent of the rock. Rarely quartz is present as small round grains. The andesites are commonly altered to chlorite, carbonate, iron oxides, epidote, serpentine, sericite, and zeolites. About 20 percent of one thin section is an isotropic substance, probably chlorophaeite, presumed to be an alteration product of a once glassy groundmass. The andesitic dikes vary considerably in texture as well as composition. Many are dense, dark greenish-gray, fine-grained rocks. Porphyritic varieties, having phenocrysts of plagioclase, hornblende, or augite, are not uncommon, and spherulitic texture is found locally.

The percents of minerals in four typical thin sections of basalt, andesite, and dacite are shown below and a chemical analysis of basalt is given in table 4. Two thin sections of a hornblende basalt dike near 765 S., 575 E. on the Windy claims (pl. 13) show hornblende phenocrysts, pleochroic from pale yellow to pale greenish-brown and pale green, and augite phenocrysts, as long as 3 mm, in a fine-grained (less than 0.25 mm) groundmass of hornblende needles, plagioclase laths, and minute octahedra of magnetite (commonly less than 0.01 mm in size). A thin section of a hornblende dacite dike near 130 N., 50 W. (pl. 13) shows abundant hornblende phenocrysts, pleochroic from pale yellow to pale greenish-brown, and sparse augite phenocrysts, in a groundmass of fine-grained hornblende, plagioclase, quartz, and magnetite. Percents of the minerals in the hornblende basalt and hornblende dacite are shown as follows:

Percents of minerals in four thin sections of basalt, andesite, and dacite, estimated by D. R. Shawe

	Hornblende basalt Windy prospects 765 S., 575 E.	*Hornblende basalt Windy prospects 765 S., 575 E.*	*Hornblende andesite Unnamed prospect No. 2*	*Hornblende dacite Windy prospects 130 N., 50 W.*
Plagioclase	40 (labradorite?)	45 (labradorite)	50 (andesine)	48 (andesine)
Augite	10	10		1
Hornblende	40	37	42	35
Magnetite	5	5	5	4
Quartz		1		12
Others, including chlorite, epidote, carbonates, goethite	5	2	3	
Total	100	100	100	100

The andesite dikes occur in sets chiefly in four areas. Within these areas the dikes trend generally eastward or slightly north of east, roughly parallel to one another, but branching is common. Contacts with wall rocks are invariably sharp. Clearly the andesite dikes were emplaced in fractures. Some of the fractures are preandesite faults, with obvious though probably small displacement shown by the offset of metamorphic rock units or potash-rich dike rocks. Most of the andesitic dikes are nearly vertical, but a few have dips as low as 40°. The fracture system was by far the most important control in their emplacement, but the pre-Cambrian foliation controlled a few of the branching dikes. The fact that many of the andesitic dikes in the pre-Cambrian area appear to intersect the Clark Mountain fault but do not cross it suggests that some postandesite movement has occurred on the Clark Mountain fault.

About six rhyolite dikes were distinguished from the andesitic group, to which they appear related structurally. These felsitic dikes occur mostly within half a mile of U. S. Highway 91, and their general easterly trend is parallel to that of the andesite dikes. The rhyolite dikes are as much as 12 feet thick and 2,000 feet long. The rhyolite is chalky white or pale gray and, like many felsitic dike rocks, it commonly has a flow structure or sheeting parallel to the walls of the dike. Thin section examination indicates that fine-grained, altered feldspar makes up 60 to 70 percent of the felsitic rock. It is probably orthoclase in large part, for it is untwinned and the refractive indices appear to be less than 1.53. Fine grains and thin veinlets of quartz constitute about 30 percent of the rhyolite. Minor constituents include apatite, leucoxene, muscovite, zircon, and blebs and veinlets of calcite and iron oxides.

AGE

The potash-rich intrusive rocks of the Mountain Pass district are of pre-Cambrian age, according to age determinations made on zircon in the shonkinite and monazite in the Sulphide Queen carbonate body.[1] On the basis of field relationships in the district and analogy with known geologic events of the surrounding region, they could logically be of any age from pre-Cambrian to early Tertiary. The potash-rich rocks cut across the pre-Cambrian foliation and are essentially nonfoliated, thus indicating the absence of regional metamorphism since their emplacement. They are cut by the Tertiary (?) andesite dikes which were emplaced in fractures. All, or nearly all, the potash-rich rocks are older than the carbonate rock emplacement.

The age of zircon in the shonkinite at the Birthday shaft has been tentatively calculated to be about 800 to 900 million years in four determinations. Four tentative age determinations based on radioactive decay products in monazite from the Sulphide Queen carbonate body range from about 900 to 1,000 million years.[1] These data indicate that both the potash-rich rocks and the carbonate rocks are of pre-Cambrian age.

The potash-rich rocks are older than most of the faults shown on the geologic map, although some preexisting faults apparently influenced the intrusions. For example, the granite dikes 3,300 feet N. 30° E. of Grover Spring, trending east across the shonkinite-syenite stock, are probably fault controlled, as a fault zone has been identified both east and west of them. This pregranite structure is roughly paralleled by the later andesite dike sets.

The rare-earth mineral deposits associated with the potash-rich rocks are unknown in rocks younger than the metamorphic complex. The potash-rich rocks have not been found in any of the Paleozoic or younger rocks, nor are extrusive equivalents of the bulk of these rocks, such as trachyte, known in the district. The nearest volcanic rocks are those of probable Cretaceous age and dacitic composition (Hewett, 1950, personal communication) in the Mescal Range south of Mescal Spring (pl. 1). These flow breccias rest on sandstone of Jurassic age and, on the west, are overridden by sedimentary rocks of Paleozoic age along the Mescal thrust. Because these rocks occupied a position above the metamorphic complex prior to a displacement of 10,000 to 12,000 feet on the Clark Mountain fault, it is possible the andesitic dikes that cut the metamorphic complex served as feeders for these extrusive rocks.

Although late Mesozoic or early Tertiary intrusive rocks are known in the surrounding region, none appear to be closely related in space or composition to the potash-rich rocks in the Mountain Pass district. Porphyritic orthoclase-rich dike rocks (granite porphyry) in the Goodsprings district have been described by Hewett (1931, p. 36, 38, 54–55), who con-

[1] H. W. Jaffe, report in preparation.

cluded, from the succession of structural events in the region, that they were intruded in late Cretaceous or early Tertiary time, probably the latter. Hewett (1931, p. 38–39) also describes dikes, classed as lamprophyres, complementary to the granite porphyry dikes and also intruded in the epoch preceding ore deposition, from three localities in the Goodsprings quadrangle. In the southwestern part of the Ivanpah quadrangle, about 35 miles southwest of Mountain Pass, Hewett (in preparation) has mapped a large body of granite near the south end of Old Dad Mountain that intrudes flow breccias somewhat like those in the Mountain Pass district. This granite is relatively rich in potash and hence more closely resembles the syenite and granite at Mountain Pass than any other known in this region. Alkalic syenite and melanite-nepheline syenite, cutting dolomite of Paleozoic age in the northern Panamint Range more than 100 miles to the northwest, have been described by McAllister (1940).

Lamprophyres and acidic dikes of the Searles Lake quadrangle, about 100 miles west of Mountain Pass, are reported to be pre-middle Miocene and post-Lower Cretaceous, probably early Eocene in age (Hulin, 1934, p. 418–419). Camptonite dikes, generally not more than 2 feet wide, intrude Carboniferous and Jurassic rocks of the northern Argus Range and granitic rocks in the hills west of Darwin, more than 100 miles northwest of Mountain Pass. Hopper (1947, p. 413) tentatively correlates these with the similar Eocene (?) dikes of the Searles Lake quadrangle described by Hulin.

STRUCTURE

FAULTS

The district is bounded on the west and north by large faults (pl. 1), and many other faults have been mapped in the district. Fault movement parallel to the foliation is shown in many places by local brecciation and zones of alteration and iron staining. Large faults that cross the pre-Cambrian structural features are traced by the offsets of pre-Cambrian rock units or later igneous rocks, as well as other common features, such as slickensided fault planes, rock alteration, silicification, abundant calcite veinlets or iron-staining, drag folds, brecciation, springs or spring deposits, and topographic expressions.

Nearly all the mapped faults strike in the northwest quadrant and dip southwestward. Three exceptions are faults mapped near Wheaton Springs that strike northwest but dip northeastward. Faults that parallel the foliation also dip southwestward, and the preferred northwesterly strike and southwesterly dips of the faults are very likely due in part to the control of pre-Cambrian foliation on later structures.

The Clark Mountain normal fault, which bounds the district on the west, is reported by Hewett (1951) to have a displacement of 10,000 to 12,000 feet near Mountain Pass. The dip of this fault ranges from 35° to 70° and probably averages about 55°. The limestone, dolomite, sandstone, and volcanic rocks west of the fault stand higher topographically than the pre-Cambrian gneisses, and the fault in many places is buried by talus beneath a steep slope of limestone, dolomite, or volcanic rocks. The rocks on both sides of the fault are altered, silicified, and iron-stained. They contain scattered sulfide minerals and have been prospected by small pits. Rare-earth minerals have not been found along the fault. Chlorite, epidote, and some calcite are conspicuous in parts of the gneiss within 1,000 feet of the fault, in a zone characterized by abundant shear planes that generally parallel the fault and in places cut the gneissic foliation. The chloritic alteration is mostly in the mafic and garnet-biotite gneisses, and some andesite dikes are similarly altered.

The three most conspicuous transverse faults in the district will be called the North, Middle, and South faults (see pl. 1).

The North fault offsets the trace of the Clark Mountain fault at least 1,200 feet, in the area about 2,400 feet north of the summit of Mohawk Hill. This transverse fault extends an unknown distance northwest of the map area and at least 4 miles southeastward from the Clark Mountain fault, passing only a few hundred feet north of the Birthday shaft. Gullies and saddles mark the trace of the North fault over part of its extent. The fault dips 65°–70° S. Considerable displacement is indicated by the abrupt truncation of the shonkinite-syenite body and associated dikes and veins near the Birthday shaft, because the potash-rich dike rocks have not been found north of the fault. One andesite dike also terminates at the fault, suggesting postandesite movement. Breccia and slickensides are exposed along the fault zone. At the saddle 1,500 feet N. 80° E. of the Birthday shaft, fractures parallel to the fault zone are distributed over a width of about 300 feet in which the rocks are altered, brecciated, and cut by many veinlets of silica and carbonate apparently without rare-earth minerals. West of this point, in the area north of the Birthday shaft, the North fault appears to split into two zones as much as 400 feet apart, between which is a wedge of pre-Cambrian gneiss.

The biotite granite gneiss and the adjoining mixed gneisses (units A and B on map of metamorphic complex, fig. 3) occupy a wider area north of North fault than south of it, and the trace of the westward-dipping Clark Mountain fault is offset relatively eastward north of the transverse fault. The apparent horizontal component of displacement, based upon the poorly defined pre-Cambrian metamorphic rock units, is south side eastward. These relationships, together with the abrupt truncation of the shonkinite-syenite stock, dikes, and carbonate veins north of the Birthday shaft, indicate that the displacement on this fault was probably thousands of feet. It is conjectured that there may have been an upward as well as eastward movement of the block south of the fault, with the maximum displacement possibly in a direction nearly parallel to but slightly steeper than the dip of the Clark Mountain fault. This interpretation is speculative, for it is based largely on the distribution of poorly defined pre-Cambrian mixed rocks and the fault has not been traced west of its intersection with the Clark Mountain fault. On most of the other large faults in the district that show horizontal component of movement, the south side has shifted eastward.

The South fault extends southeastward from a point on the Clark Mountain fault, southeast of Grover Spring, and passes about 1,500 feet north of the Windy prospects. This fault is marked by topographic depressions and saddles and is evident from the differences in pre-Cambrian rocks on the two sides and the truncation of shonkinite and granite dikes. The main belt of rare-earth and thorium deposits (fig. 9) is displaced laterally about 6,300 feet by this fault.

The Middle fault has been traced from the vicinity of the highway maintenance station southeastward more than 2 miles to a point just north of the granite body on Mineral Hill. The fault dips 80° SW. to vertical, and the block southwest of the fault is inferred to have moved southeastward and probably upward relative to the northeast side. The actual displacement is not known, but the horizontal component of movement is possibly a mile. The granite on Mineral Hill and the shonkinite-syenite body southeast of the highway maintenance station may have originally been parts of the same mass, separated by the fault movement. The granite of Mineral Hill possibly represents the lower part of this faulted composite mass which solidified slightly later than the shonkinite-syenite part. The dikes of granite that cut the shonkinite-syenite body and radiate northward from it may thus be genetically related to the granite of Mineral Hill. The displacement along the Middle fault is also indicated by the relative positions of pre-Cambrian units and andesite dikes on both sides of the fault. The set of andesite dikes that cuts through the shonkinite-syenite body northeast of Grover Spring extends eastward to the fault, then is apparently displaced nearly a mile to the northwest, whence it continues eastward south of Wheaton Wash.

The Middle fault is poorly exposed northwest of the highway maintenance station, but very likely it passes not far southwest of the Sulphide Queen carbonate body, and parallel fractures that are probably related to this fault zone have been found in the area west of the carbonate body. The fault may therefore cut the carbonate body at depth. Because the footwall block north of the fault is believed to have moved relatively downward, as well as horizontally, there is a possibility of repetition of the carbonate ore body under the gravels in the area west of Mexican Well. Although this structural picture involves a number of assumptions, and the original extension to depth of the carbonate body is not known, the gravels west of Mexican Well may cover some rare-earth mineral deposits.

The two parallel granite dikes that cut the shonkinite-syenite body 3,300 feet N. 30° E. of Grover Spring were emplaced in fractures along and parallel to a fault zone, and this fault zone is therefore dated as probably postsyenite and pregranite. This east-trending fault zone extends westward from the granite dikes and eastward to the point where it is cut by the Middle fault. East of the Middle fault, the east-trending fault zone may be represented by the silicified fault north of Wheaton Wash (3,500 feet N. 70° E. of the highway maintenance station).

Some of the faults in the district are marked by such features as drag folds, breccia, gouge, and slickensides. The pre-Cambrian foliation in many places is curved to near parallelism with the faults. At one place on the fault south of the granite mass on Mineral Hill, drag folds having amplitude of about 12 feet, plunging down the 50° S. dip of the fault, indicate nearly horizontal movement of the south side southeastward. The fault that extends about 500 to 2,500 feet northwest of the Windy prospects is marked by quartz 2 feet thick that is locally brecciated. The fault that trends slightly north of east, just north of Wheaton Wash, is similarly silicified, the quartz vein being as much as 5 feet thick. The gneiss near faults is commonly altered and stained to a reddish, yellowish, or purplish brown.

AGE OF THE FAULTS

At least five periods of faulting are known in the Mountain Pass district. The earliest recognizable age of faulting is pre-Cambrian, and the latest is post-Tertiary. Zones of movement during pre-Cambrian time are indicated by dragfolds and by breccia cemented by granitic gneiss. Faults younger than the pre-Cambrian gneisses but older than the shonkinite-syenite are difficult to establish, although the potash-rich rocks were probably controlled in part by northwest-trending faults, in addition to the foliation of the metamorphic rocks. Fault movements no doubt occurred about the time of the intrusion of the potash-rich dike rocks. Many faults and shear zones cut the shonkinite, syenite, and granite, but locally contain carbonate minerals, barite, and rare-earth- or thorium-bearing minerals, and thus formed earlier than the deposition of these minerals in the shear zones.

Another episode of faulting is shown by the fractures in which the andesite dikes were emplaced, along some of which displacement occurred. The andesite dikes cut the potash-rich intrusive bodies and the rare-earth mineral deposits, dating the fracturing as post-mineralization and preandesite.

Many of the faults are postandesite, because the andesite and rhyolitic dikes are displaced by the faults. The felsite dike about 800 feet south of Mexican Well is cut by a fault that trends N. 20° E. Andesite dikes in the set that trends eastward from the shonkinite-syenite body 3,000 feet N. 70° E. of Grover Spring are apparently displaced about a mile by the Middle fault, which extends southeastward from the highway maintenance station.

The facts that many andesite dikes approach or intersect the Clark Mountain fault from the east, and that none has been observed to cross the fault suggest that there has been considerable postandesite movement on the Clark Mountain fault. Near the Clark Mountain fault the rocks are altered and silicified; andesite, as well as older gneiss and shonkinite, is altered and contains such secondary minerals as chlorite, calcite, and epidote. The Clark Mountain fault cuts the Mescal thrust, along which Paleozoic sedimentary rocks are thrust over Cretaceous (?) volcanic rocks; hence both these faults are younger than the volcanic rocks. According to Hewett (in preparation), the Clark Mountain fault about 15 miles north of the district is overridden by the Mesquite thrust fault, approximately parallel to the Mescal thrust, and accordingly was formed between the two thrusts. These thrust faults are believed to be Laramide; that is, post-Middle Cretaceous, possibly early Tertiary or Late Cretaceous in age.

SPRINGS

Springs in the district are related in part to the faulting. Mescal Spring, Grover Spring, and the spring midway between them, issue about 100 to 200 feet south of the Clark Mountain fault from a greenish-gray zone of altered volcanic rocks. Garden Spring is in a wash where it crosses an apparently small fault that trends northeast and dips about 70° NW. A northwest-trending fault dipping 80° NE. is apparently responsible for Wheaton Springs. Several faults are exposed in the vicinity of Mexican Well, which is in a wash. The spring about 4,000 feet S. 10° E. of the highway maintenance station is alined with a number of small faults, constituting a fault zone, extending S. 60° E. from the spring.

Several small tufa deposits in the district indicate former springs, and some of these are near faults, as the one about 1,400 feet N. 70° E. of the Birthday shaft, another 3,000 feet S. 30° E. of the highway maintenance station, and another about 1,000 feet S. 60° W. of the granite body of Mineral Hill where the fault crosses the wash. Other tufa deposits that are within 200 feet of known faults are found near the bend in the wash 1 mile due west of Wheaton Springs settlement, and just east of the same wash 1,500 feet south of this point. The tufa in these deposits cements fragments of various other rock types, and iron oxide stains are common in rocks nearby.

MINERAL DEPOSITS

The rare-earth minerals occur in deposits characterized by abundant carbonate minerals, barite, and quartz. These constituents occur in three principal types of deposits: the Sulphide Queen carbonate body, which is 2,400 feet long and as much as 700 feet wide; the many tabular veins an inch to about 20 feet thick; and the mineralized shear zones, in which the carbonate minerals, barite, quartz, hematite, goethite, and other minerals form many thin stringers and films in zones several feet thick.

The principal carbonate-rich body, with many appendages and satellitic bodies, is shown in plates 4 and 8. The name Sulphide Queen carbonate body is applied to this deposit because of its proximity to the old Sulphide Queen gold mine and mill.

About 200 veins and mineralized shear zones are shown on the district map (pl. 1). They are as much as 20 feet thick and 600 feet long, but many are only a foot or less in thickness. It is estimated that the surface area of the Sulphide Queen carbonate body is more than 10 times larger than the sum of all the other exposed veins in the district.

The carbonate rock includes many varieties of calcite, ankerite, dolomite, or siderite rocks, containing various amounts of barite, strontian barite or barian celestite, quartz, bastnaesite, parisite, and small quantities of many other minerals including crocidolite, chlorite, biotite, phlogopite, muscovite, aegirine, sphene, allanite, monazite, magnetite, goethite, hematite, galena, pyrite, chalcopyrite, tetrahedrite, malachite, azurite, cerussite, aragonite, wulfenite, fluorite, strontianite, apatite, thorite, cerite, and sahamalite. The proportions of minerals range widely even in the same deposit. A rough estimate of the principal constituents in the carbonate rock of the district, in percent, is carbonate minerals, 60; barite, 20; rare-earth-bearing fluocarbonates, 10; and quartz and other silicates, 10.

The specific gravity of the carbonate rock ranges from 2.7 for rocks rich in calcite to 4.0 for rocks rich in barite and bastnaesite. The carbonate rock rich in rare-earth minerals and barite is clearly higher in specific gravity than any of the metamorphic or igneous rocks of the district, and this feature has proved to be an important guide in prospecting.

AREAL DISTRIBUTION

The distribution of carbonate rocks, veins, and prospect pits in the district is shown on the geologic map (pl. 1), and is outlined in figure 9. The known rare-earth and thorium deposits are most abundant in a belt, in places 3,000 to 4,000 feet wide, that trends northwest from the southeast corner of the mapped area to the vicinity of the Birthday shaft. This belt is offset by the transverse faults and appears to be terminated by the transverse fault north of the Birthday shaft.

Although no large fault has been mapped in this belt, many small northwest-trending faults are exposed for short distances, and these locally contain rare earths and thorium. The number and size of the veins and carbonate rocks in the belt appear to be related to the potash-rich intrusive rocks, for the greatest concentration is in and along the southwest side of the largest shonkinite-syenite mass. The mineralized shear zones in this belt cut the shonkinite-syenite body and related dikes, as well as carbonate veins; yet they locally contain rare earths, thorium, barite, and other constituents of the veins. Hence faulting occurred after the main period of deposition of the carbonate rocks, but some circulation of mineralizing solutions took place during or after this faulting.

Among the deposits south of U. S. Highway 91, there is an apparent spatial association between the richer parts of mineralized shear zones and the Tertiary(?) andesitic dikes that cut across these zones (see pl. 13 and pl. 1). Because many andesitic dikes in the district are wholly unrelated to the rare earth-thorium deposits, it is clear that the magmatic source of the andesite was not the source of these rare elements. The spatial association may be fortuitous, or it may indicate that aqueous emanations accompanying the andesitic intrusions served as vehicles of redistribution and concentration of some of the rare elements already present in carbonate rocks and other rocks along the shear zones.

The concentration of veins in the belt shown in figure 9 does not necessarily mean that veins are absent from other parts of the district. The close relationship that seems to exist between the rare earth-thorium deposits and the potash-rich intrusive rocks suggests possible occurrences near other dikes outside the belt shown in figure 9, such as the granite of Mineral Hill and the shonkinite-syenite body a mile northwest of it. A few thin carbonate veins were noted near the granite on Mineral Hill, but rare-earth minerals are not known to occur in them.

DEPOSITS AT NORTH END OF DISTRICT

A few veins composed chiefly of calcite and quartz occur in the area north of the North fault, which is a few hundred feet north of the Birthday shaft. One prospect pit exposes a fault that is silicified and iron-stained, but no rare-earth or thorium minerals have been found in these deposits.

DEPOSITS NEAR CLARK MOUNTAIN FAULT

Many pits have been dug in silicified and altered rock along the Clark Mountain fault. Seams of malachite, azurite, and iron oxides have been found associated with some of the silicified and altered rock, but no mines have been developed along the fault or immediately east of it. Silicified zones with sparse pyrite, chalcopyrite, and malachite have also been explored in the gneiss east of the fault, such as a vein 3,200 feet due north of Kokoweef Peak and 75 feet from the fault, and another within 100 feet of the fault 1.8 miles northwest of Kokoweef Peak. The Carbonate King and Mescal mines, in limestone within 1,000 feet west of the fault, have been mined for lead, zinc, and silver, and stibnite is relatively abundant at the Mescal mine, but no relation is evident between these and the rare-earth mineral deposits. The Clark Mountain fault, an interthrust normal fault, preceded and controlled some of the metal deposits in the district, but not necessarily the rare-earth mineralization. Fluorite is abundant in several deposits in Paleozoic dolomite north of Clark Mountain, but it is not known in deposits south of Clark Mountain and west of the Clark Mountain fault.

DEPOSITS NORTH OF U. S. HIGHWAY 91

Known rare-earth and thorium mineral occurrences north of Highway 91 are concentrated along the southwest side of the shonkinite-syenite stock in both gneiss and the intrusive body. Many of the veins in this area, between the Birthday shaft and the Bullsnake prospect, contain rare earths and are somewhat radioactive. Tiny brownish-red grains of thorite have been found in several deposits, and a little galena is present in some. The large carbonate body southwest of the old Sulphide Queen gold mine is the greatest concentration of rare-earth metals known in the district, although parts of

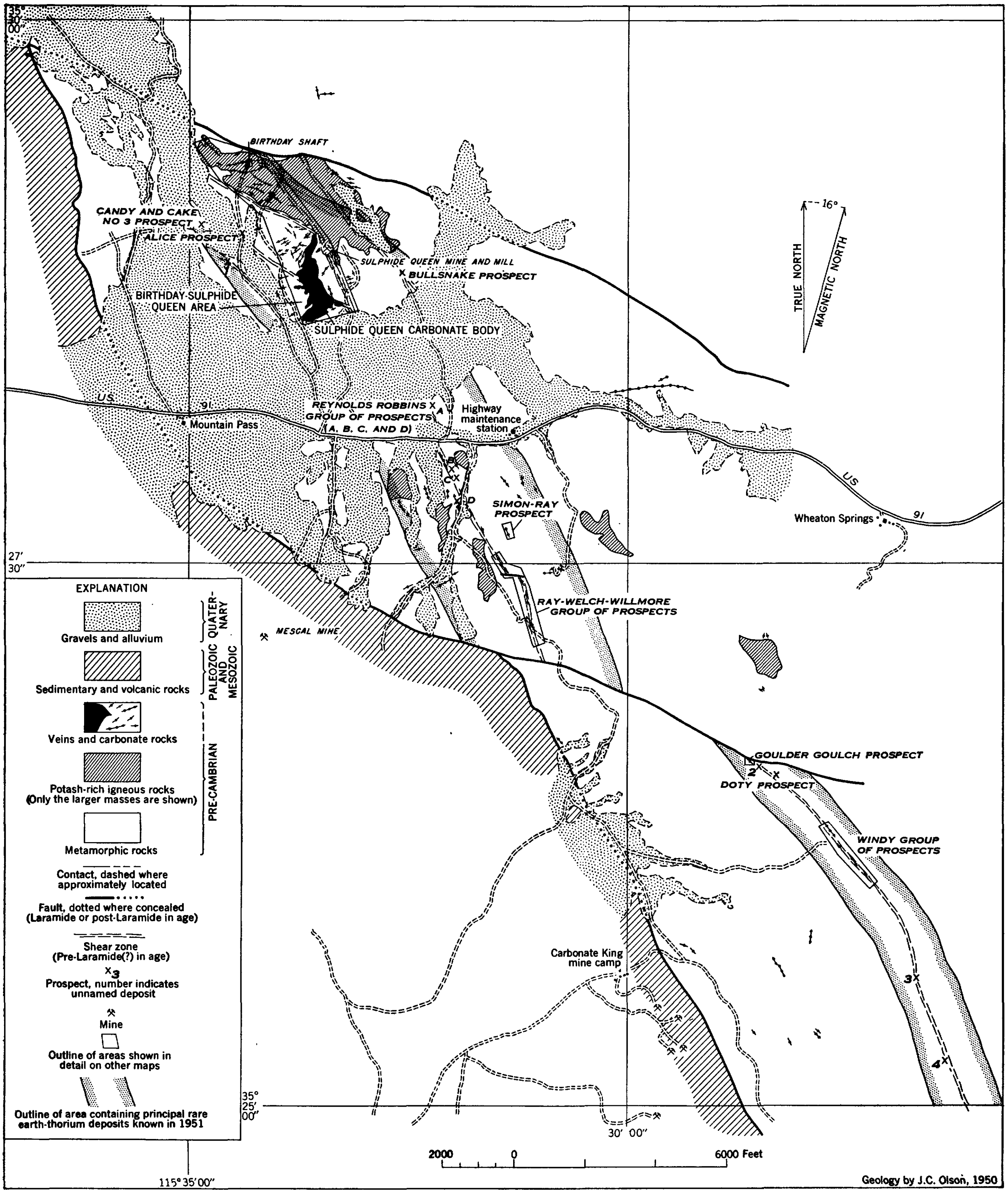


FIGURE 9.—Map of Mountain Pass district, showing distribution of veins and carbonate rocks.

some thin veins, such as the original discovery vein near the Birthday shaft, are equally rich or richer.

The area west of the Birthday shaft and the Sulphide Queen carbonate body is a broad, gently sloping surface largely covered by gravels and alluvium. Bedrock is exposed in some areas, and in these exposures 10 or more prospect pits have been dug. Some of these pits are in unmineralized gneiss; others expose shear zones along which the gneiss is chloritized and cut by many veinlets of calcite, quartz, hematite, and goethite. Some of the shear zones are radioactive. Carbonate veins exposed in this area are a few inches to 2 feet thick, but no large bodies were noted.

In the area north of the highway and east of the Bullsnake prospect and Mexican Well, faults and silicified fault zones, locally stained by copper carbonates, have been prospected by several pits, but no rare-earth or thorium minerals have been found in this area.

DEPOSITS IN CENTRAL PART OF DISTRICT, SOUTH OF U. S. HIGHWAY 91

No rare-earth-bearing veins have yet been found in that part of the area south of U. S. Highway 91 and northeast of the Middle fault, which passes near the highway maintenance station. Veins and mineralized shear zones occur in the area southwest of this fault and north of the South fault which extends southeastward from Grover Spring, especially in the belt outlined in figure 9. Bastnaesite and thorite have been found, for example, in the veins in the Reynolds Robbins prospects 600 feet northwest of Mexican Well and 2,300 feet south of it. The deposits in the area near these prospects are classed as mineralized shear zones. As exposed in the prospect pits, many closely spaced, steeply dipping, subparallel fracture-surfaces are coated with hematite, goethite, silica, barite, and iron-bearing carbonate, in zones about 5 or 10 feet wide that are commonly radioactive. Carbonate veins 0.5 to 3 feet thick occur in some of these shear zones. One vein exposed in a pit about 2,300 feet south of Mexican Well is about 2.5 feet thick. Bastnaesite and thorite have been found in this vein, as well as barite, calcite, and quartz. Six of seven thin sections of the vein from this pit contained one or more grains of bastnaesite. The vein has a rough planar structure caused by streaks of the finer grained calcite-barite-quartz matrix between coarser eye-shaped barite grains oriented parallel to the walls.

Mineralized shear zones that in places are radioactive occur in the vicinity of the two shonkinite-syenite bodies northeast of Grover Spring and are shown on the geologic map of the district (pl. 1) as veins. The radioactivity appears to be due largely to thorium and is mostly in seams associated with hematite and goethite. Small grains of thorite have been found locally in these zones.

Breccia fragments of gneiss and dark biotite syenite or shonkinite are enclosed in a bastnaesite-bearing carbonate vein 3 feet thick, 2,500 feet due south of the highway maintenance station.

DEPOSITS IN AREA NEAR THE RATHBURN PROSPECTS

At the Rathburn prospects, 3,800 feet S. 20° E. of the highway maintenance station, several west- to northwest-trending silicified faults occur in a zone about 250 feet wide. The largest mine opening is an inclined shaft, presumably sunk in prospecting for gold, extending about 50 feet down the 60° dip of a 1- to 2-foot quartz vein. The quartz vein and adjoining silicified wall rock contain a little azurite, malachite, pyrite, copper-bearing sulfides, and iron oxides. Other faults nearby in the same fault zone are silicified and stained by secondary copper- and iron-bearing minerals, and some of these have been prospected by small pits. Rare earth-thorium minerals have not been found in the Rathburn prospects, and the rare-earth mineralization is probably of a different age from that of copper and gold. A few grains of pyrite, copper-bearing sulfide, and malachite have been found in several other localities, such as several prospect pits about 2,000 feet northeast of Grover Spring and another 1,000 feet south of the highway maintenance station.

The area between the Rathburn prospects and the granite body on Mineral Hill contains very few small carbonate or quartz veins. A little prospecting has been done in shonkinite, syenite, or granite dikes which are slightly more radioactive than the adjoining gneiss but of no known value. Several carbonate veins, about 2 feet thick on the average, occur in the gneiss around the granite body on Mineral Hill, but rare earth minerals have not been found in them.

DEPOSITS SOUTH OF THE SOUTH FAULT

In the pre-Cambrian block south of the South fault, which passes 1,500 feet north of the Windy prospects, veins occur in several areas, as shown in plate 1 and figure 9. The veins in this area that are known to contain rare earths or thorium lie in a belt that extends from a point about 3,000 feet N. 50° W. of the Windy prospects, through the Windy prospects, thence S. 25° E. to the abnormally radioactive sheared gneiss at the southeasternmost prospect shown on the geologic map.

Several of the veins in this belt contain small, shiny, red grains of thorite. Bastnaesite has been identified in the Windy prospects. The vein exposed in the Windy No. 1 pit, which is the northwestern one of the Windy prospect pits as designated on the geologic map, is 40 to 50 inches thick. In a bulldozed area 150 feet to the southeast along the strike, the vein pinches to less than 4 inches thick. The vein in the pit strikes about N. 45° W. and dips 70° SW. and was apparently emplaced in a fracture steeper than the 60° dip of the foliation of the enclosing migmatite and granitic gneiss. The vein is composed chiefly of quartz, barite, calcite, and goethite. Sparse grains of bastnaesite were found in 5 of 8 thin sections from this vein. Fluorite is a minor constituent in the Windy No. 1 pit and in other exposures to the southeast. Just a few feet southeast of the Windy No. 1 pit, the vein lies alongside and parallel to a shonkinite dike 1 foot thick. The dike was sheared, parallel to its strike, after its emplacement, forming many shear planes in the shonkinite and gneiss, and the vein was deposited in a fracture alongside the shonkinite dike. Similar thin shonkinite dikes are exposed at irregular intervals along the strike of this zone for 2,800 feet to the southeast.

At a prospect shown in the southeast corner of the district geologic map, a radioactive shear zone in chloritized gneiss is exposed in a small outcrop in a wash. A thin section of the radioactive sample is composed largely of microcline and quartz of the granitic gneiss, with a little biotite, chlorite, zircon, and magnetite. Secondary or introduced minerals, which occur chiefly along seams and fractures in the gneiss, include quartz, chlorite, hematite, goethite, calcite, and thorite (?).

Several veins in the general area 3,300 to 4,800 feet N. 40° E. of Kokoweef Peak contain considerable iron-stained carbonate mineral, probably siderite, and quartz. Smaller carbonate veins, mostly only a few inches thick, occur in the area about 2,200 feet southeast of these. In both these areas, very little prospecting has been done and no rare earth-thorium minerals have been found.

MINERALOGY

The minerals of the veins and carbonate rocks of the district are listed below according to chemical composition:

Carbonates:
- Calcite
- Dolomite
- Ankerite
- Siderite
- Strontianite
- Aragonite
- Cerussite
- Malachite
- Azurite
- Sahamalite

Sulfates:
- Barite (strontian)
- Celestite (barian)

Fluocarbonates:
- Bastnaesite
- Parisite

Oxides:
- Quartz
- Hematite
- Magnetite
- Goethite
- Melaconite

Silicates:
- Crocidolite
- Chlorite
- Phlogopite
- Biotite
- Muscovite (sericite)
- Aegirine
- Sphene
- Allanite
- Cerite
- Thorite

Sulfides:
- Galena
- Pyrite
- Chalcopyrite
- Tetrahedrite
- Bornite

Phosphates:
- Monazite
- Apatite

Fluoride:
- Fluorite

Molybdate:
- Wulfenite

CARBONATES

Calcite is the most abundant carbonate mineral in the deposits. Dolomite and ankerite are also abundant, and siderite is less common but is abundant in some veins. Cerussite is found locally at the north end of the Sulphide Queen carbonate body. Some of the carbonate minerals contain manganese, as suggested by the dark-brown weathered surfaces of some of the carbonate rocks. Weathering of the iron-bearing carbonates causes limonitic staining in and near the veins. The unweathered carbonate minerals range in color from white to cream, gray, or pale pink. A white to cream carbonate mineral was identified as ankerite on the basis of optical properties of specimens from the Birthday area. Later spectrographic tests by E. L. Hufschmidt of the Geological Survey confirmed this identification and indicate calcium and magnesium as the major constituents, and between 1 and 10 percent iron.

Some of the carbonate minerals occur in grains an inch or more across, but most of the carbonate minerals are in finer grained aggregates. The carbonate minerals make up at least half of the material in most veins, but they range from nearly 0 to 100 percent. Calcite predominates in most of the Sulphide Queen carbonate body, which is about 60 percent carbonate mineral, and commonly occurs as anhedral interlocking grains about 0.5 mm in diameter.

Much of the carbonate of the veins is evenly iron-stained and is probably ankerite. The index determined for the carbonate in a vein in the Birthday-Sulphide Queen area (2000 S., 630 W. on grid, pl. 6) is 1.70 ± 0.005 for nO. The index is that of parankerite (Mg: Fe: : 2: 1), according to Winchell (1951, p. 114); the reddish stain on weathered surfaces indicates that it is probably iron-bearing (parankerite) rather than manganese carbonate with similar index.

Strontianite has been found in the Sulphide Queen carbonate body and in a vein on the Birthday No. 6 claim. The strontianite cements a breccia of barite-carbonate rock in the Sulphide Queen carbonate body and appears to be one of the late vein minerals (Hewett, 1953, personal communication).

A new rare-earth carbonate mineral, composed of carbonate of magnesium, iron, and cerium earths, has been named sahamalite (Jaffe, Meyrowitz, and Evans, 1953). Sahamalite has thus far been found only in an area about 150 feet in diameter near the southwest end of the Sulphide Queen carbonate body.

Azurite and malachite that occur sparsely along fractures were perhaps derived through the weathering of copper-bearing sulfides such as chalcopyrite and tetrahedrite.

SULFATES

Barite in many veins is the most abundant noncarbonate mineral. It ranges from 0 to 65 percent of most veins, although some veins 1 or 2 inches thick are largely barite. Barite constitutes as much as 65 percent locally, and averages 20 to 25 percent, of the Sulphide Queen carbonate body. The barite contains variable amounts of strontium, and some of the mineral is nearer çelestite than barite in composition. The grain size of barite ranges widely, and is commonly about 0.5 to 1 cm. The barite in the veins and in the Sulphide Queen carbonate body typically occurs as coarse tabular or oval grains of white to pink or red color. Some of the barite has curved cleavage planes, and polysynthetic twinning is seen commonly in thin section. It is particularly conspicuous in the strontian barite. In addition to the coarse grains, barite also occurs as fine-grained veinlets with or without quartz, along shear planes or fractures cutting other minerals of the carbonate rock. On rough weathered surfaces, the barite commonly stands in relief above the carbonate minerals. In the Sulphide Queen carbonate body, many of the barite crystals, when broken, show lighter colored cores which have good prismatic cleavage, in contrast to the dull fine-grained outer zones.

In the Sulphide Queen carbonate body (pl. 5), the darker red variety of barite seems to be associated with the areas of abundant crocidolite and chlorite. Barite near silicified zones is predominantly white, although both pink and white barite occur in silicified carbonate rock. The cause of the difference between pink and white barite is not apparent in most thin sections, although some of the pink barite contains small inclusions of hematite (?). Some white barite is rimmed and veined by pink barite. The high strontium content of some of the barite has not been correlated with the differences noted in thin sections.

Barian celestite forms abundant crystals as much as an inch across in the large ankeritic vein in the Birthday area near 1,430 feet south, 800 feet west (pl. 4). The mineral is commonly pale pink or flesh colored, although some is almost white. Cleavage is perfect in three mutually perpendicular directions, and curved cleavage surfaces are the rule. Polysynthetic twinning is conspicuous and is coarse enough to be visible megascopically. X-ray examination by J. M. Axelrod of the U. S. Geological Survey indicates the mineral is a member of the barite group, intermediate between barite and celestite. Qualitative chemical tests made in the laboratory of the U. S. Geological Survey indicate sulfate, barium, and strontium. Independent spectrographic tests made by the Smith-Emery Company indicate rare earths as minor constituents. Optical properties determined by Jewell Glass, of the U. S. Geological Survey, are as follows:

Optic sign ---------------------------------- positive
2V ---------------------------------- about 50°
Maximum extinction $Z\wedge(110)$-------- about 53°
Indices of refraction:
$X=1.625$
$Y=1.627$ $nZ-nX=0.008$
$Z=1.633$

FLUOCARBONATES

The rare-earth minerals thus far recognized in the veins and carbonate rocks include the fluocarbonates bastnaesite and parisite, and monazite, allanite, cerite, and sahamalite. Of these the most abundant is bastnaesite, which constitutes 5 to 15 percent of much of the Sulphide Queen carbonate body and locally exceeds 60 percent. In the thin veins, the bastnaesite content ranges from 0 in most of the veins to rare concentrations of 60 percent or more. The bastnaesite is light tan to honey colored, pale cream, yellow, greenish yellow, reddish yellow, and reddish brown.

Bastnaesite crystallizes in the ditrigonal, dipyramidal class of the hexagonal system. Most of the crystals are tabular (pl. 2*D*), flattened parallel to (0001). Rarely in high-grade veins (pl. 6*C*) the crystals are 4 inches long, but most are less than an inch, and in the large carbonate body many of the bastnaesite tablets are no more than 1 mm in length. The "bow-tie" structure of the tabular crystal masses is locally well developed. In addition to the tabular form, small hexagonal prisms of bastnaesite are found locally in the large carbonate body. Fracture surfaces are irregular and have a resinous luster. An indistinct prismatic cleavage is present. Bastnaesite from Mountain Pass does not appear to have such perfect basal cleavage as that reported by Glass and Smalley (1945, p. 605) for bastnaesite from New Mexico. Lacroix (1922, p. 297–299) describes two varieties of bastnaesite crystals, one with a basal parting or cleavage, and one without this cleavage. In common with bastnaesite from other localities, the Mountain Pass bastnaesite has a hardness of about 4½ and a specific gravity of about

5. The mineral is soluble in strong sulfuric acid with evolution of hydrofluoric acid and carbon dioxide.

Some pale yellow bastnaesite is slightly pleochroic with absorption Z>X. The refractive indices of the bastnaesite from the Birthday area have been determined by Jewell Glass, and are compared to other determinations of the refractive indices of bastnaesite cited by Glass and Smalley (1945, p. 610).

TABLE 6.—*Optical constants of bastnaesite*

Constant	Sweden	Belgian Congo	New Mexico	Pikes Peak	Jamestown, Colo.	Madagascar	Mountain Pass, Calif.
n^o	1.7220	1.722	1.718	1.717	1.716	1.717	1.722
n^ϵ	1.8235	1.823	1.819	1.818	1.817	1.818	1.823
$n^\epsilon - n^o$	.1015	.101	.101	.101	.101	.101	.101
Optic sign	+	+	+	+	+	+	+

A chemical analysis of impure bastnaesite, believed to contain about 5 percent very fine-grained quartz, and a little barite and carbonate minerals, from the Birthday claims is given in table 7, and a spectrographic analysis in table 8.

TABLE 7.—*Chemical analysis of impure bastnaesite, Birthday discovery vein*

[M. K. Carron, analyst]

Ce_2O_3	32.47	SO_3	0.62
$(La,Di)_2O_3$	36.70	K_2O	.04
CO_2	18.31	Na_2O	.06
F	6.88	H_2O-	.22
SiO_2	4.42		102.98
BaO	2.20	Less O⇌F	2.90
CaO	.70		
MgO	.36		100.08

TABLE 8.—*Spectrographic analysis for minor elements in impure bastnaesite from the Birthday area in percent*

[E. L. Hufschmidt, analyst]

Major constituents		Minor constituents	
Ce, La, Nd	>5	Ba, Ca	0.X
Si	1–5	Al, Mg, Y	.0X
		Fe, Sr	.00X
		Cu, Mn	.000X

Fluorine has been detected spectrographically by the CaF^+ band by George Petretic of the U. S. Geological Survey. The quantitative spectrographic analysis of rare earths separated chemically from bastnaesite (99 percent pure) from the Birthday area was determined by H. J. Rose, with the following results: La_2O_3, 29.6 percent; CeO_2 (chemical), 50.3; Nd_2O_3, 14.3; Pr_6O_{11}, 4.4; Sm_2O_3, 1.3; Y_2O_3, not detected.

The formula of bastnaesite from other districts analyzed is $RFCO_3$, in which R indicates the rare earths, largely cerium, lanthanum, neodymium, and praseodymium. Rare-earth oxides form from 73.59 percent to 76.80 percent of bastnaesite. X-ray powder diffraction patterns of the bastnaesite from the Birthday area, made in the laboratory of the U. S. Geological Survey in Washington, coincide with X-ray patterns of bastnaesite from other localities.

Bastnaesite is a rare mineral and was known from only about 10 localities in the world before the Mountain Pass discoveries. The data for many of these have been summarized by Glass and Smalley (1945). The mineral is found in granite and syenite pegmatites; in contact metamorphic zones; in veins with other carbonate minerals, fluorite and barite; and in alluvial deposits. Most of the known occurrences are summarized in table 9.

TABLE 9.—*Occurrences of bastnaesite*

Locality	Notes on occurrence
United States:	
Jamestown, Colo	Associated with cerium silicates in a contact zone between schist and granite.[1]
Pikes Peak, Colo	A minor mineral in granite pegmatites.[1]
Gallinas Mountains, N. Mex	In veins with barite, barytocelestite, calcite, fluorite, and other minerals.[1]
Sweden:	
Riddarhyttan district	In a contact zone with cerium silicates, bastnaesite is a secondary mineral. This deposit was the only previously known commercial deposit of primary cerium ore.[1]
Finbo	With albite and red feldspar (Hintze, 1930).
Madagascar:	
Torendrika-Ifansina	In aegirine syenite pegmatites (LaCroix, 1922).
Mt. Marotompona	Alluvial, probably originally from pegmatite (LaCroix, 1922).
Russia: Kyshtim	With cerium silicates in contact zone with alkali syenite.[1]
Belgian Congo	Alluvial gravels, source unknown.[1]
China	With fluorite, barite, and iron ore (Ho, 1935).

[1] Summarized by Glass and Smalley (1945), from original sources.

TABLE 9.—*Occurences of bastnaesite*—Continued

Locality	*Notes on occurrence*
Alaska: Salmon Bay area	Veins containing hematite, magnetite, sulfides, thorite, monazite, zircon, parisite, dolomite-ankerite, feldspar, quartz, fluorite, apatite, topaz, and other minerals, in graywacke, sandstone, shale, and limestone breccia; associated with lamprophyre and alkalic dikes (Houston, Velikanje, Bates, and Wedow, 1953, p. 6-10).
Canada:	
Rexspar mine, Birch Island, British Columbia.	Sparse grains associated with fluorspar, carbonate, pyrite, celestite, and dark mica, in replacement bodies along certain layers in metasedimentary and metavolcanic (?) rocks.
Greenland: Narsarsuk	Pegmatite associated with syenitic rocks.

Parisite, a fluocarbonate of calcium and rare earths, has been identified in the Mountain Pass district in and near the Sulphide Queen carbonate body, where it occurs locally in the carbonate rocks and one granite sample (H. W. Jaffe, 1952, personal communication). A lamellar intergrowth of bastnaesite and parisite is shown in plate 7*A*. Further detailed mineralogical study will probably show the parisite to be more widely distributed than now known.

OXIDES

Quartz occurs in the veins in various proportions, generally from 5 to 40 percent but ranging from 0 to 100 percent. Some veins that are essentially all quartz are as much as 6 feet thick. They are found chiefly near granite bodies and along several silicified fault zones, such as the one north of Wheaton Wash and another northwest of the Windy prospects. One quartz vein as much as 6 feet thick and several hundred feet long cuts shonkinite and metamorphic rocks near the Birthday shaft. The quartz veins are probably of several ages.

Quartz in the rare-earth and thorium deposits is a late mineral and is found in irregular veinlets cutting older minerals; as euhedral grains in places zoned with dusty opaque material, in barite; and as euhedral crystals lining vugs. Patches of interlocking anhedral quartz grains occur in brecciated and mineralized gneisses, and may have formed by recrystallization of original quartz of the gneisses.

Late quartz that appears to postdate the thorium mineralization occurs in radioactive granite at 2165 S., 111 W. on the map grid of the Birthday-Sulphide Queen area (pl. 4). Stained joint surfaces in the granite show radioactivity as much as 0.9 milliroentgen per hour. In thin section hematite and probably thorite are seen on the joint surfaces, and dilation veinlets of hematite, thorite, goethite, and possibly manganese oxides occur in the granite. Quartz has replaced part of the feldspar and the thorite-bearing veinlets in the granite. Quartz grains extend unbroken through the veinlets, and movement along some of the veinlets has resulted in shadowy remnants of the veinlets in the quartz, in line with unreplaced segments of the veinlets on either side of the quartz. Microscopically the quartz which crosscuts the veinlets appears identical with quartz presumed to be primary in the granite.

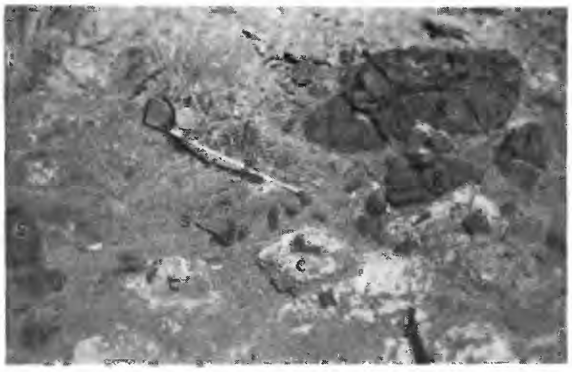
Hematite is a common mineral in the mineralized shear zones, carbonate rocks, and disseminated in igneous rocks. Hematite is seen in thin sections as minute, anisotropic, bright orange-red hexagonal plates with high relief, and as larger opaque plates. The plates range from a small fraction of a millimeter to several millimeters across, and deepen in color with increase in size. Irregular grains of hematite are scattered through all of the thorite-bearing mineralized shear zones, locally constituting as much as 25 percent of the vein, and dusty hematite is developed in varying amounts in thorite. Hematite also occurs in skeletal crystals of earlier ferromagnesian minerals in the altered gneisses. Hematite plates have developed preferentially around the edges of masses of fluorite in the vein near 485 S., 420 E. on the map grid of the Windy group of prospects (pl. 13).

Magnetite is common in the igneous rocks and also occurs locally in carbonate rock, such as at 3523 S., 290 E. on the map grid of the Birthday-Sulphide Queen area (pl. 4). Shiny black magnetite octahedra as much as 1 mm in size are embedded in carbonate.

Almost all the mineralized shear zones, and some of the carbonate veins, contain several percent of goethite, derived in large part through the weathering and alteration of iron-bearing minerals such as siderite, ankerite, biotite, pyrite, and magnetite. Melaconite is found with chalcopyrite underground in the recent workings at the Ray-Welch-Willmore group of prospects (975 S., 490 E. on grid, pl. 13).

SILICATES

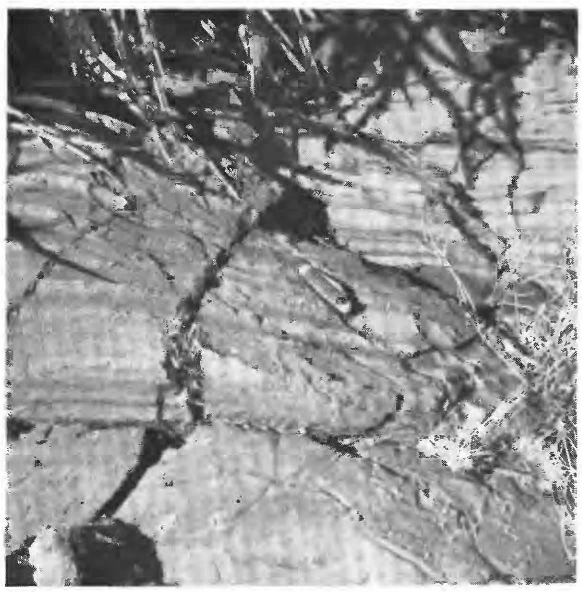
The carbonate rocks contain a variety but only a small quantity of silicate minerals in addition to quartz, such as crocidolite (the fibrous blue soda-amphibole), phlogopite, biotite, muscovite (sericite), chlorite, aegirite, allanite, cerite, sphene, and thorite. Typical contact metamorphic minerals such as diopside, idocrase,



A

B

C



D

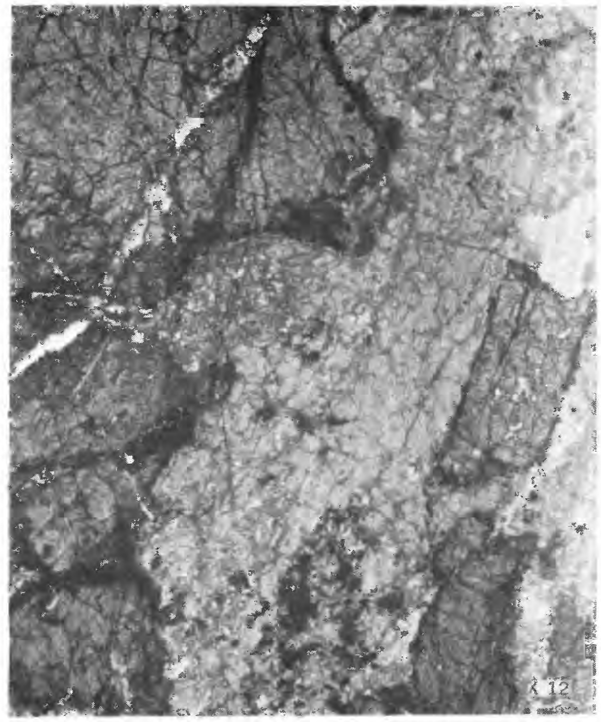
STRUCTURE OF CARBONATE ROCKS, MOUNTAIN PASS DISTRICT, CALIFORNIA

A. Breccia fragments of feldspathic rocks in Sulphide Queen carbonate body: *g*, gneiss; *s*, syenite, which is dark because of phlogopitic reaction rim; *c*, fragments of older carbonate rocks in younger.

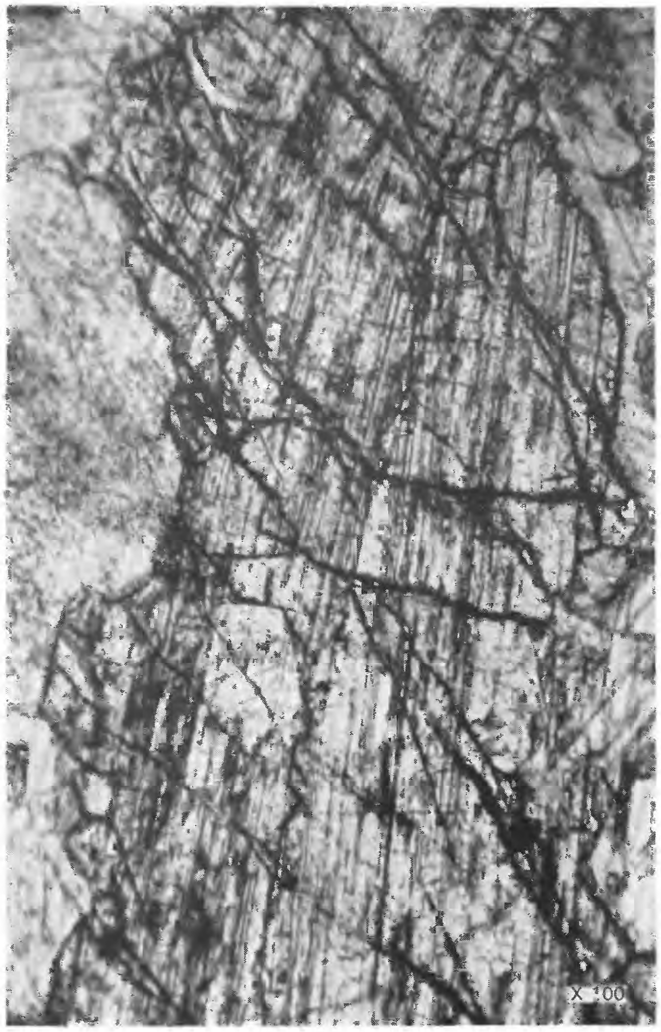
B. Streaked barite foliation, Sulphide Queen carbonate body.

C. Outcrop of bastnaesite-rich vein, Birthday area, showing bastnaesite crystals in relief above carbonate-barite matrix. By J. C. Olson.

D. Layering in satellitic carbonate mass east of north end of Sulphide Queen carbonate body.



B



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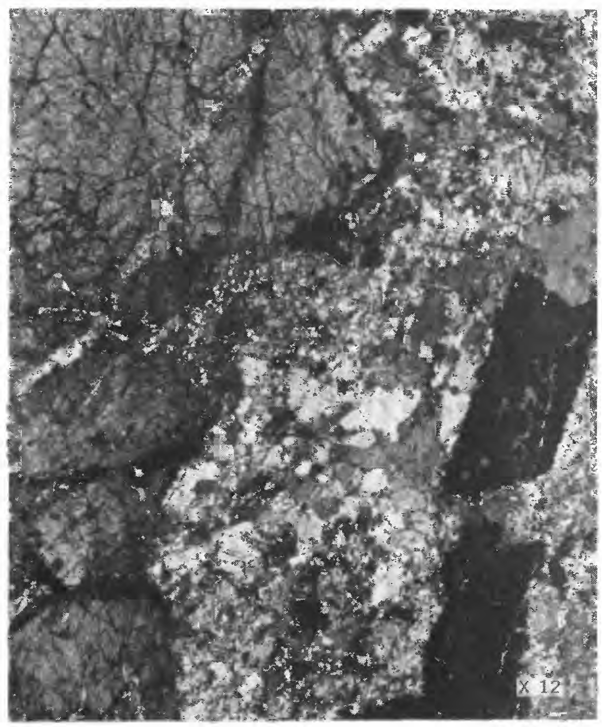

C

H. W. Jaffe

PHOTOMICROGRAPHS OF BASTNAESITE LAMELLAE AND BROKEN CRYSTALS, MOUNTAIN PASS DISTRICT, CALIFORNIA

A. Lamellar intergrowth of bastnaesite and parisite in carbonate rock, northern part of Sulphide Queen carbonate body. Bastnaesite lamellae have higher relief than parisite.

B. Broken bastnaesite crystals showing finer grained barite filling the interstices. Plane polarized light.

C. Same subject and magnification as *B*. Crossed Nicols.

and garnet are absent from the Mountain Pass carbonate rocks.

Veinlets of crocidolite occur in the various potash-rich igneous rocks and the carbonate rocks, and in gneisses adjacent to them. In some of the thicker crocidolite veins, about half an inch thick, the amphibole fibers are oriented perpendicular to the walls of the veinlet. In the carbonate rocks the crocidolite fibers are aggregated in subparallel orientation along shear planes which bend around the barite grains, imparting a foliation to the rock. Crocidolite examined in index oils has a refractive index for gamma between 1.65 and 1.66, moderate birefringence, parallel extinction, and anomalous blue interference colors; it is length-fast, and is pleochroic, from green to bluish-green parallel to elongation, and pale brownish-green to pale-violet normal to elongation.

Phlogopite and biotite have formed at contacts, and around the edges of small fragments of feldspathic rock such as syenite or gneiss, by reaction between the carbonate material and feldspathic rock. The dark mica also occurs as scattered flakes in calcite and along or near shears in the carbonate rock. Phlogopite is also found in shonkinite in several places along the rare-earth- and thorium-bearing veins, and in altered, mineralized gneiss. For example on the Windy prospects (1334 S., 990 E. on the map grid, pl. 13), pale greenish-brown phlogopite was noted in altered gneiss that also contains allanite and thorite.

Some of the phlogopite shows color-mottling that suggests compositional differences within the crystals. Some phlogopite in the Sulphide Queen carbonate body has anomalous absorption and some is zoned. The cores of the zoned mica show normal absorption; the rims are anomalous, with Y and Z colorless and X orange-brown; and intermediate zones are colorless. A similar mica, described by Jakob (1924), contains 8.30 percent Mn_2O_3 and 1.55 percent Na_2O. The anomalous absorption of these phlogopites may be due to considerable manganese content, since manganese is present in some of the ferruginous dolomite in the Sulphide Queen carbonate body. Biotite, with X pale greenish brown, Y and Z reddish brown, occurs sparsely in the carbonate rock.

Chlorite is found in fractures and interstitial to breccia fragments in crushed gneisses in the mineralized shear zones. Chlorite also occurs, with hematite and goethite, as skeletal remnants of earlier ferromagnesian minerals in mineralized gneisses.

Fine-grained sericite (?) found in part of the Sulphide Queen carbonate body is strongly birefringent, biaxial negative, 2V about 25°, pale yellow, and of platy and fibrous habit. Sericite has developed along shears locally in mineralized granite gneiss, and is found sparsely in feldspars in gneiss near the veins.

Minor amounts of allanite are found in granite, syenite, and carbonate rocks, in late shears in several of the carbonate veins, and associated with strontian barite in late veins cutting the Sulphide Queen carbonate body. The allanite is prismatic and is strongly pleochroic, from green or light greenish brown to dark brown or reddish brown. On the Windy group of prospects, near 1335 S., 990 E. on the map grid (pl. 13), allanite in a thorium-bearing shear zone in gneiss is irregularly colored and appears gradational to epidote in single crystals. Several percent of epidote is present in this altered gneiss, and aggregates of epidote, allanite, hematite, chlorite, quartz, and goethite are alteration products of ferromagnesian minerals of the gneiss.

Prismatic allanite (?), pleochroic from yellowish and greenish brown to dark reddish brown, is seen sparsely in a thin section from an andesitic dike near the south edge of the Mountain Pass district. The allanite in this altered andesitic rock is invariably associated with carbonate which has replaced phenocrysts and is undoubtedly not an original constituent of the dike.

Judging from the weak radioactivity associated with much of the allanite of the veins, the allanite probably contains less than 1 percent thorium.

Cerite has been identified in a vein on the Birthday No. 6 claim.

Thorite occurs in small, dark-red to yellowish-brown, lustrous grains, as much as 3 mm but mostly 1 mm or less in diameter, in veins and radioactive shear zones. The greatest concentrations of thorite in the district are in mineralized shear zones rather than in well-defined carbonate veins, but thorite has been found in some of the carbonate veins, such as the narrow vein of very fine-grained carbonate near the Sulphide Queen carbonate body at 3523 S., 1090 E. on the map grid (pl. 4). This vein contains disseminated, yellowish-brown, elongate prisms of thorite as long as 0.5 mm, with bastnaesite, hematite, and magnetite.

Almost all the thorite in the mineralized shear zones in gneiss is in shear planes filled with hematite, goethite, sericite, chlorite, quartz, and carbonates. Thin sections show that much of the thorite is crowded with minute specks of hematite and goethite. The iron oxide is in the outer parts of many thorite crystals, and in some crystals it forms concentric zones. Some thorite contains so much hematitic dust as to be almost opaque.

In four thin sections the thorite ranges from clear yellowish-brown prismatic crystals to almost opaque hematite-crowded blebs. In autoradiographs of these thin sections, exposed 41 days, the emulsion above the thorite crystals is surrounded by many radiating alpha tracks. Analyses of thorium-rich vein material show as much as 6 percent ThO_2.

Much of the Mountain Pass thorite probably contains water in its crystal structure and hence might properly be called hydrothorite or thorogummite. Most of the thorite is anisotropic, with low and mottled birefringence, and is uniaxial positive. Some thorite contains irregular isotropic patches, or is wholly isotropic, and is metamict. The refractive index of some thorite from 190 S., 205 E. on the map grid of the Windy group of prospects (pl. 13) is near 1.71, which is in the range of metamict thorite. There is doubtless a range in degree of metamictization, water content, and refractive index of the thorite. Many grains of thorite are surrounded by radiating, anastomosing cracks, in the host quartz and feldspar, perhaps due to expansion of the thorite during its hydration.

Much of the thorite is square or octagonal in cross section, and sections cut parallel to the *c* crystallographic axis of a crystal show typical elongate prisms doubly terminated with pyramids whose apices have several obtuse and acute angles. Many grains are terminated with an obtuse pyramid on one end and an acute pyramid on the other. Length to width ratios of the thorite crystals range from about 3:2 to 7:2.

Thorite from the galena-bearing vein at 2482 S., 238 E. on the map grid of the Birthday-Sulphide Queen area (pl. 4) occurs as minute, yellowish, almost isotropic, tetragonal crystals about 0.05 mm in size. Unlike most of the thorite crystals in the district, these are enclosed in small spheres of quartz, 2 to 4 times the diameter of the thorite crystals, in a mass of irregular hematite grains, goethite, and small quartz anhedra.

Most thorite, being metamict, requires ignition before showing thorite patterns in X-ray powder photographs. An X-ray powder photograph of a thorite-rich sample from the vein at 190 S., 205 E. on the map grid of the Windy group of prospects (pl. 13) shows a thorite pattern without preheating.

SULFIDES

Sulfide minerals occur in small quantities in the carbonate rocks and adjacent altered wall rocks. Pyrite is the most abundant and is common underground in the Birthday and Sulphide Queen mines. Weathering of pyrite may account for some of the iron oxides in and near the veins at the surface. Galena is a widespread but minor constituent. Chalcopyrite and bornite have been identified at a copper prospect near the south end of the district. Chalcopyrite is found associated with melaconite underground in the recent workings at the Ray-Welch-Willmore group of prospects, near 975 S., 490 E. on the map grid (pl. 13).

PHOSPHATES

Monazite has not been found in the highly radioactive veins which contain abundant thorite, but it occurs in the Sulphide Queen carbonate body, chiefly in the dolomitic parts, where local concentrations have radioactivity as much as 0.8 milliroentgen an hour. The subhedral to euhedral monazite crystals are brown, reddish brown, or yellowish brown. In one vein west of the north end of the Sulphide Queen carbonate body, monazite crystals several millimeters in diameter occur in a calcite veinlet in rock composed of barite and brown-weathering carbonate. Analyses of monazite collected near 4275 S., 230 E. on the map grid of the Birthday-Sulphide Queen area (pl. 4), indicate a range in ThO_2 content between 1 and 3 percent. Radioactive age determinations of this monazite indicate a tentative age of about 900 to 1,000 million years.[2]

Apatite forms about 4 percent of the shonkinite, and it also occurs in other igneous rocks and locally in the Sulphide Queen carbonate body in amounts of a fraction of a percent.

OTHER MINERALS

Fluorite is a minor constituent in some of the igneous rocks, and locally in the veins and the large carbonate body in amounts that rarely exceed 1 percent. On the Windy group of claims, one weakly radioactive vein (485 S., 420 E. on map grid, pl. 13) contains several percent of purple to white fluorite, the color being most intense along cleavages and fractures. Some masses of almost pure fluorite are several centimeters thick, and small euhedra are enclosed in the sideritic(?) carbonate of the vein.

A few crystals of wulfenite (lead molybdate) have been found in one vein at the Birthday shaft.

RADIOACTIVITY

The radioactive minerals occur in mineralized shear zones characterized by abundant hematite and goethite, and in the carbonate rocks. The radioactivity is due almost entirely to thorium and its decay products. The strongest radioactivity is attributable chiefly to thorite, and to a lesser extent to monazite which occurs in and near the Sulphide Queen carbonate body.

Radioactivity was measured in the field with a Geiger-Mueller counter and recorded in milliroentgens (mr) per hour. References in this report to mr-per-hour readings may be compared with the average background reading of 0.03 to 0.05 mr per hour in the Mountain Pass district. Observations on the distribution of radioactivity are given in the descriptions of the principal thorium-bearing deposits, such as the Sulphide Queen

[2] H. W. Jaffe, report in preparation.

carbonate body and the Ray-Welch-Willmore and Windy groups of prospects, and isorad lines are shown in plates 4 and 13.

The radioactivity of the vein samples ranges from 0.004 to 0.55 percent equivalent uranium.[3] The uranium content of these samples, determined chemically, is low, the highest value being 0.020 percent uranium. Thorium oxide, however, is more than 2 percent of some samples.

Autoradiographs of four thin sections of thorium-rich veins, after an exposure of 41 days, show the radioactivity due to thorite. In addition there are clusters of sparse unoriented alpha tracks in the photographic emulsion immediately over clear grains of bastnaesite, indicating that the bastnaesite is also somewhat radioactive and probably contains a fraction of a percent thorium. Some of the bastnaesite in the Mountain Pass district probably contains little or no thorium. A separation was made of bastnaesite from the Birthday claims, and a nearly pure fraction, tested radiometrically, assayed 0.013 percent equivalent uranium. An autoradiograph of one specimen of this bastnaesite shows that the radioactive material occurs along many small fractures and cleavage planes in the coarse bastnaesite, rather than being uniformly distributed in the crystal lattice. The uranium was not determined chemically, but in accordance with the other data it is assumed that most of the radioactivity is due to thorium.

Readings taken with a portable ratemeter at about 100 stations in the Sulphide Queen carbonate body, and samples analyzed in the laboratory, indicate that radioactivity is relatively uniform in this body. The intensity of the radoactivity generally is 2 to 4 times that of the gneiss; radiometric equivalent uranium values range from 0.001 to 0.018 percent. Chemical analyses show that the principal source of the radioactivity is thorium, as the ThO_2 content ranges from 0.01 to about 0.16 percent.

STRUCTURAL FEATURES

The veinlike bodies composed chiefly of carbonate minerals, barite, and quartz strike dominantly northwest and almost without exception dip steeply. The veins in the shonkinite-syenite stock near the Sulphide Queen mine are parallel or intersect at sharp angles, as though controlled in large part by a system of steeply dipping fractures. The veins in the metamorphic rocks were controlled partly by the foliation. Most of the mineralized shear zones strike northwest, perhaps influenced partly by the foliation, but they commonly cut the foliation.

MINERALIZED SHEAR ZONES

The mineralized shear zones, as distinguished from the well-defined veins, are zones about 1 to 20 feet thick characterized by parallel shear planes, gouge, and breccia. The rocks near the zones are altered, chloritized, iron-stained, and laced with many veinlets or stringers of carbonate mineral, quartz, crocidolite, and barite. Many of these shear zones contain bastnaesite and thorite locally. In addition to the many veinlets, commonly a fraction of an inch thick, that characterize many of the shear zones, some contain thicker veins such as the 4-foot vein at the Windy No. 1 pit. All gradations exist between well-defined veins several feet thick and zones of sheared gneiss with only thin veinlets of introduced material.

The content of rare earths and thorium varies markedly at different points across the width of a mineralized shear zone. Samples of some veins and shear zones are rich in rare-earth and thorium minerals, but the mineralization is most persistent where well-defined veins are present. As exposed in prospect pits, the individual shear zones do not seem persistent along the strike, but rather are irregularly staggered or in echelon in a zone 200 feet or more wide, such as the Windy and Ray-Welch-Willmore groups of prospects (pl. 13).

The radioactive shear zones have been referred to by prospectors as "burnt rock," in allusion to the reddish or yellowish-brown color, caused by hematite and goethite along fractures, and the radioactivity present along some of the zones. In the mineralized shear zones, quartz and feldspar, which are abundant original constituents of the metamorphic rocks, are commonly crushed and milled to rounded grains less than 0.5 mm in diameter which form an indurated matrix containing larger grains of quartz and feldspars. In some thin sections, lines of dusty inclusions in quartz, parallel to fractures in adjacent potash feldspar, suggest that quartz has recrystallized more readily than feldspar under stress. The mylonitization, the fine-grained recrystallized quartz, and the strain shadows common along shear planes attest to the great stress involved in the development of the shear zones along which rare earths, thorium, and other materials were subsequently introduced.

Alteration products found along the mineralized shear zones and the veins include epidote, prehnite, sericite, chlorite, carbonates, leucoxene (?), hematite, goethite, and probably clay minerals. Epidote, prehnite, sericite, carbonates, and chlorite are abundant also in some of the metamorphic complex far from the thorium-bearing veins, and may have developed through

[3] Equivalent uranium (eU), expressed in percent, is a measure of the radioactivity of a sample, regardless of the source element to which the radioactivity is due; it corresponds to the percent of uranium, in equilibrium with its daughter products, that would yield an equivalent amount of radioactivity.

processes independent of those forming the veins. The ferromagnesian minerals in the mineralized shear zones are commonly replaced by chlorite, calcite, hematite, goethite, and other vein minerals.

CARBONATE ROCKS AND VEINS

CONTACT RELATIONS

Contacts between the veins and the host rocks are generally sharp, although the wall rocks are commonly altered within a few inches or a few feet of the contacts. One manifestation of the alteration is a bleaching of the biotite, accompanied by development of iron oxide spots in or near the biotite. Other iron-bearing minerals may be altered, and veinlets of carbonate, quartz, hematite, goethite, and barite penetrate the wall rocks. Replacement of wall rocks occurred locally but is thought to have played a subordinate role in the development of the veins.

INCLUSIONS

Breccia veins found at several places in the district contain scattered fragments of granite, syenite, shonkinite, or gneiss in a matrix dominantly carbonate. The feldspathic fragments typically are rimmed by dark phlogopite or biotite formed by reaction with the carbonate material. In one breccia vein, 2,600 feet due south of the highway maintenance station, dark biotite syenite fragments are enclosed in pink, bastnaesite-bearing carbonate matrix. Another breccia vein, 1,000 feet N. 70° E. of the old Sulphide Queen shaft, is a carbonate vein 5 to 7 feet thick in shonkinite, is exposed over a length of 150 feet, and dips 70° S. Fragments of shonkinite and syenite make up about 15 to 25 percent of the vein.

Breccia fragments of various older rock types are abundant locally in the large Sulphide Queen carbonate body, chiefly near the margins. These fragments are composed of gneiss, syenite, shonkinite, and older carbonate rock in younger (pl. 6*A*). Some of the fragments are essentially in place, and the angular feldspathic wall-rock fragments are but little rotated, but in other places well-rounded rock fragments of several rock types are assembled, thus indicating that they have moved from their original positions. The feldspathic fragments are typically coated with a reaction rim of dark phlogopite or biotite, implying the addition of magnesium and water. Another thin breccia vein occurs between the north end of the Sulphide Queen carbonate body and the Sulphide Queen shaft. This vein is 2 inches to 2 feet thick, strikes N. 50° W., and dips 50° SW. The vein is composed of calcite, barite, quartz, fluorite, monazite, parisite, apatite, and magnetite, and it encloses fragments of granite, pre-Cambrian gneiss, and pegmatite which have the typical reaction rims of dark mica.

INTERNAL STRUCTURAL FEATURES

The most obvious structural feature of the carbonate rocks is the alinement of mineral grains, chiefly barite, from a fraction of a centimeter to several centimeters thick, parallel to the walls of many of the dikelike carbonate bodies and best developed at the contacts. Inclusions within the carbonate rock have deflected the lines of mineral grains. The barite grains are commonly eye-shaped as in an augen gneiss, and the elongate grains parallel the walls of the vein. Shear planes curve around the barite grains and in many places contain crocidolite fibers oriented parallel to the shear planes. Foliation manifested by barite and crocidolite in late wavy shears is better developed in the Sulphide Queen carbonate mass than in the veinlike bodies.

Layering due to variation in grain size and concentration of opaque minerals, forming layers of carbonate-barite rock about an inch thick, is well exposed in the satellitic mass just east of the north end of the Sulphide Queen carbonate body. Opaque minerals are concentrated in thin bands in several thin sections of carbonate rock.

Although the layered nature of the carbonate bodies does not indicate the manner of formation of these bodies, the exceptional development of foliation close to contacts, and around inclusions within the carbonate rock, strongly suggests that laminar flow caused the layering. Hence, movement of some of the carbonate rock within its enclosing walls, at least in a plastic if not a partially fluid state, seems certain.

The mineral content of the tabular veinlike deposits varies markedly from place to place, both along and across the strike, but there is no apparent systematic variation or zoning in the deposits. At the Robbins prospect 600 feet N. 40° W. of Mexican Well, a crudely banded vein 6 to 24 inches thick, dipping 65° SW., is exposed over a length of 40 feet N. 20° W. Adjacent to the hanging wall is a 1- to 3-inch zone of coarse tabular bastnaesite crystals with a preferred orientation parallel to the contact. The brown finer grained central part of the vein also contains bastnaesite but in smaller quantity and finer grains. Along the footwall the vein is a somewhat porous rock in which cavities about 0.1 inch in diameter are lined with silica. This type of zoning is not found in any other veins examined.

PARAGENESIS

The paragenesis of the vein minerals is incompletely known at present. The time of formation of a certain mineral in one vein may not coincide with that of the same mineral in another where the overall compositions of the veins are as varied as in the Mountain Pass district. Some minerals such as bastnaesite, quartz, and fluorite appear to have formed at more than one time or over a prolonged period.

In paragenetic sequence, the carbonate minerals appear to be among the oldest, as well as youngest, minerals in the deposits. In the Sulphide Queen carbonate body, crocidolite and bastnaesite are concentrated along some shear planes in calcite and dolomite, giving the rock a foliation. Late calcite replaces barite and occurs in veinlets cutting the other common minerals. Near the southern corner of the Sulphide Queen carbonate body, coarse rhombic dolomite is fractured, and the interspaces are filled with calcite, barite, plumose dolomite, and bastnaesite, thus indicating early dolomite. Calcite and quartz were deposited at several stages, as shown by veinlets of one cutting another. The aragonite in veins traversing the Sulphide Queen carbonate body is apparently the latest carbonate mineral deposited.

Siderite appears to be an early mineral in the Birthday veins. In iron-rich veins the calcite and barite are commonly younger than the siderite and bastnaesite, but in veins composed largely of calcite, barite, and bastnaesite, these minerals appear to be contemporaneous.

As seen in thin section the bastnaesite generally has crystal outlines, and is very rarely altered or replaced by other minerals. In some veins, fractured bastnaesite crystals are cemented and partially replaced by later carbonates, quartz, goethite, and barite (pl. 7*B* and *C*). Elsewhere, unbroken crystals afford no evidence of the early formation of bastnaesite. In the thin veins, the bastnaesite has good crystal form, and the fractures in it are filled by the other common minerals, suggesting a relatively early age. In the Sulphide Queen carbonate body, the small bastnaesite crystals are mostly interstitial to the coarser augen of barite, and are commonly associated with calcite, quartz, and locally crocidolite in and near shear planes that curve around the barite grains. In some parts of the mass, fine-grained quartz-bastnaesite aggregates fill fractures in coarse barite grains. These features suggest that bastnaesite, like the other common minerals, has formed at more than one stage in the paragenetic sequence.

In parts of the large carbonate body, fractures in large barite crystals are filled with a later aggregate of barite, bastnaesite, and quartz. Locally, coarse grains are partly replaced by calcite or quartz, and selective replacement of barite by quartz was noted in several thin sections. In one thin section from the vein at the Windy No. 1 prospect, which is at the north end of the Windy group of prospects (pl. 13), barite surrounds quartz crystals and lines cavities as though deposited after the quartz. These examples indicate that barite was deposited at several stages.

Quartz is commonly a late mineral, but some appears to have crystallized throughout much of the period of vein formation. The quartz commonly occurs in thin veinlets, alone or with barite, carbonate, or bastnaesite, cutting earlier-formed carbonate rock and locally replacing certain minerals. Some tabular or oval barite grains appear to be selectively replaced by quartz. The quartz in several thin sections of rock near the south end of the large carbonate body contains three or four concentric lines parallel to crystal outlines, apparently due to growth of successive layers in cavities formed by leaching of calcite, which is absent from this rock. In other sections, calcite surrounds quartz crystals.

The fluorite typically occurs as tiny grains less than 1 mm in diameter along seams, veinlets, and fractures; this indicates its crystallization late in the paragenetic sequence. However, some fluorite in veins of siderite, barite, bastnaesite, and quartz appears to have formed contemporaneously with the major vein minerals.

GEOLOGIC AGE OF THE CARBONATE ROCKS

The carbonate rocks cut across and include pre-Cambrian metamorphic rocks, shonkinite, syenite, and granite. The relation of carbonate rocks to the late shonkinitic dikes is not conclusive in every case, but in those where the evidence is clear the carbonate rocks cut across the dark fine-grained shonkinitic dikes. The andesitic dikes, of probable Tertiary age, cut sharply across the carbonate rocks.

Radioactive age determinations on monazite from 4272 S., 229 E. (pl. 4), near the east edge of the Sulphide Queen carbonate body, of about 900 to 1,000 million years, indicate a pre-Cambrian age for the carbonate rock.[4]

DESCRIPTIONS OF SELECTED DEPOSITS

SULPHIDE QUEEN CARBONATE BODY

The Sulphide Queen carbonate body is an irregular, north-striking mass about 2,400 feet long and averaging 400 feet wide. Its maximum width is 700 feet in the southern part and it is less than 200 feet wide at the north end (pl. 4). Apophyses of carbonate rock extend from the main body into the enclosing gneiss, and satellitic bodies of carbonate rock as long as 200 feet occur close to the larger mass. Inclusions of gneiss and igneous rocks as much as 150 feet long occur in the carbonate body close to its border. Average radioactivity of the large carbonate body ranges from 0.06 to 0.10 mr per hour, and is due largely to the thorium in monazite.

[4] H. W. Jaffe, report in preparation.

ATTITUDE OF CONTACTS

The contacts between gneiss and carbonate rock at the north end of the mass dip about 60° W. The gneiss foliation east of the north tip approximately parallels the contacts of the carbonate body, but at the west edge of the body and in gneiss inclusions nearby, the gneiss foliation strikes perpendicular to the contact (see pl. 4). The discordance of this northern part of the carbonate body suggests emplacement of the carbonate along a line of dislocation in the gneiss. The parallelism in the gneiss inclusions suggests the carbonate rock may have been emplaced along a zone of multiple shears. The east contact between gneiss and carbonate rock dips 30°–50° W., approximately the attitude of the gneiss foliation in this area. Two holes that were drilled in the east edge of the carbonate body by the Molybdenum Corporation of America pass from carbonate rock into gneiss, confirming the westerly dip of the east contact (see cross section *F—F′*, pl. 4).

Toward the south end, the east contact steepens. The south contact is nearly vertical, dipping alternately north and south. Contacts at the southwest tip are obscure. Attitudes of the gneiss foliation are variable but generally discordant along the south contact. Between the main mass and the large carbonate satellite east of the south end of the carbonate body the gneiss foliation is concordant with the contact. Leaves of gneiss penetrate the southeast edge of the carbonate body roughly parallel to the contact.

The attitude of the very irregular west contact of the carbonate body is not clearly known. North of the fault that cuts the central part of the mass (pl. 4), large apophyses extend from the carbonate body into the gneiss. They dip 45°–65° NW., approximately parallel to the large mass. Similar leaves south of this fault dip 80° W., and 25° W. A hole drilled by the Molybdenum Corporation of America in the gneiss east of the southernmost carbonate leaf passes into carbonate rock at a depth of 10 feet, and indicates a 25° W. dip of the contact here (see cross section *G—G′*, pl. 4). In general the west contact seems to dip moderately west. The irregularity of the west contact is partly due to the close accordance of its attitude with the slope of the hillside. The gneiss foliation on the west side of the carbonate body strikes northwest and is discordant to the contact.

The large podlike carbonate satellites near the north end of the main body dip essentially parallel to that end of the mass. The satellitic body west of the central part of the body dips steeply southeast.

LITHOLOGIC TYPES

The Sulphide Queen carbonate body has been divided into three map units, and the carbonate rock throughout the Sulphide Queen-Birthday area (pl. 8) has been classified into these rock types, in order of decreasing age: brown ferruginous dolomitic rock, gray carbonate-pink barite rock, and silicified carbonate rock. Each of these lithologic units shows several varieties, and gradations exist between them.

FERRUGINOUS DOLOMITIC ROCK

Reddish-brown to grayish-brown fine-grained dolomitic rock, containing barite and monazite, occurs in satellite bodies near the north end of the carbonate body and as inclusions, a few inches to many feet in diameter, in the gray carbonate-pink barite rock. The ferruginous dolomitic rock is fine-grained, dense, and has a specific gravity ranging from 2.85 to 3.56. On weathered surfaces the carbonate is grayish brown, probably from iron and manganese oxides; fresh fracture surfaces are gray to light brownish gray. Magnetite, and hematite pseudomorphs after pyrite, as well as monazite and fine-grained pink barite, stand in relief to the carbonate on weathered surfaces. Much of the rhombic dolomite rock in the southwest part of the large carbonate body is similar in appearance to the pink barite-gray calcite rock, but is brown on weathered surfaces. The brown dolomitic rock along the northwest edge of the body, and in a similar area near the southwest tip, grades indefinitely into the surrounding gray calcitic rock.

Optical and X-ray data obtained by Jaffe (1952, personal communication) indicate that rhombic and plumose dolomite is the principal carbonate mineral in the ferruginous rock, but calcite predominates in the monazite-rich rock at 4272 S., 229 E. of the map grid (pl. 4), and other ferruginous dolomite rocks contain minor amounts of calcite. Some of the plumose dolomite of inclusions in the northern part of the carbonate body contains a few percent manganese. Manganese is abundant at the two shallow shafts known as the Manganese No. 1 and Manganese No. 2 in an area, near the north tip of the carbonate mass, which contains abundant ferruginous dolomite inclusions.

The ferruginous dolomitic rock contains monazite in various amounts. The peripheral distribution of the ferruginous dolomitic rock accounts for the similar pattern of monazite distribution shown in plate 8. Some of the monazite-bearing rocks also contain bastnaesite and parisite, for example at 3960 S., 505 E. of the map grid, and contain about 0.5 to more than 10 percent rare-earth oxides. In the southwest corner of the carbonate body the indefinite area of brown carbonate rock, in which are several ferruginous inclusions, contains barite, bastnaesite, parisite, and sahamalite (Jaffe, 1952, personal communication) but no monazite. According to Jaffe, part of the dolomite in this area is plumose and part occurs as distinctive rhombs that are fringed by rare-earth minerals with interstitial barite and invaded by calcite and barite.

Autoradiographs made by Hewett of sawed pieces of the manganese-bearing dolomite rock indicate the presence of radioactive minerals, in part associated with bastnaesite, which include monazite and possibly thorite.

Apatite occurs in the monazite-bearing carbonate rocks. One specimen from a breccia zone between a large syenite inclusion and ferruginous dolomitic rock, at 4213 S., 543 E. of the map grid, consists essentially of monazite, apatite, and magnetite (Jaffe, 1952, personal communication). Acmitic aegirine was noted by Jaffe in a specimen of monazite-bearing ferruginous dolomite at 4040 S., 507 E. of the grid (pl. 8).

Three samples of ferruginous dolomite rock, from the satellitic body east of the north end of the Sulphide Queen carbonate mass, are composed chiefly of the dolomite, fine-grained pink barite, dark mica in flakes parallel to the layering and in small clots, and crocidolite and chlorite in subparallel shear planes. In thin section, the layering is seen to be a result of different concentrations of carbonate, barite, and an opaque mineral, probably magnetite.

GRAY CALCITE-PINK BARITE ROCK

The most abundant rock type of the Sulphide Queen carbonate body consists of 40 to 75 percent calcite, 15 to 50 percent barite, and 5 to 15 percent bastnaesite, with lesser amounts of the other minerals. Specific gravity of the rock ranges from 2.72 to 3.56. Anhedral interlocking calcite grains averaging a millimeter in size enclose subrounded crystals of barite, averaging 1 cm, and in places as much as 4 cm, in diameter, and much smaller subhedral to euhedral hexagonal prisms of bastnaesite. Alinement of barite grains (pl. 6*B*, fig. 10*b*), and veinlets of barite in shear planes cutting calcite and earlier barite grains, are apparent in outcrop and thin section. Crocidolite and chlorite occur in most of the rock, and in places they are abundant. In much of the rock the rounded to ragged barite crystals are surrounded by aggregates of calcite, small euhedral to subhedral bastnaesite grains (fig. 10), granular barite, goethite, and quartz. Most barite crystals are free of bastnaesite, but a few contain one or two bastnaesite crystals close to their edges. In many places calcite replaces barite grains. Barite in much of the rock is replaced by later barite with the development of patch-patterns, best evidenced under crossed nicols by the different optic orientations of the patches. Some bladed barite crystals transect earlier barite and calcite grains.

In certain streaks the calcite is fine-grained (less than 0.5 mm) and appears to have been pulverized by movement. Scattered minute blebs in larger calcite crystals suggest recrystallization of a fine-grained part to form coarser interlocking grains. Twin lamellae and cleavage directions are subparallel locally in the carbonate rock, indicating the orienting influence of shear stress.

The bastnaesite is predominantly subhedral to euhedral in hexagonal prisms, but is partly anhedral (fig. 10*a*) and rarely corroded and replaced by later minerals (fig. 11*a*). Some crystals are zoned (fig. 11*b*). In many places bastnaesite crystals are broken and veined by calcite and barite (figs. 10*c* and 11*a*); a few bastnaesite crystals are bent. Although generally scattered at random through carbonate (fig. 12*c*), the bastnaesite is in places (fig. 12*d*) alined parallel to calcite lamellae in other parts of the thin section. Control of bastnaesite development by shear zones is indicated commonly by the abundance of bastnaesite in the vicinity of sericite-filled shear planes. Fine-grained sericite (?) occurs in sheared portions of the carbonate rock and is invariably associated with brown and yellowish-brown goethite or hematite.

Phlogopite occurs in the gray calcite-pink barite rock, especially as reaction rims around feldspathic inclusions, and sparse biotite occurs in the carbonate rock. Phlogopite veined by bastnaesite is shown in figure 12*b*. Crocidolite and chlorite are found in late shear planes (see figs. 10*d* and 12*a*) that parallel the barite shear foliation.

Quartz is rare in the calcite-barite rock, and it replaces barite or calcite. Figure 11*a* shows a sieve-textured hexagonal quartz grain containing a residual subhedral bastnaesite grain and residual irregular calcite blebs.

Other minerals present in small quantities in the barite-calcite rock are apatite; rare grains of thorite (?), a yellow-brown, metamict or partly metamict mineral of high relief; allanite in the red barite (fig. 10*c*); zircon; galena (fig. 12*a*); hematite (figs. 10*c*, 12*b*, and 12*d*); magnetite; pyrite (fig. 12*b*); and leucoxene (?). Jaffe (1952, personal communication) has identified monazite in several specimens from gray calcite-pink barite areas near the southern border of the carbonate mass.

SILICIFIED CARBONATE ROCK

The silicified carbonate rock consists predominantly of bastnaesite, barite, and quartz, with small amounts of calcite, hematite and goethite, sericite, galena, and pseudomorphs of hematite after pyrite. Bastnaesite, in amounts as great as 60 percent, and goethite impart a yellow color to the rock. The barite in the silicified rock is commonly white and rarely pink, in contrast to the pink barite in other parts of the carbonate body.

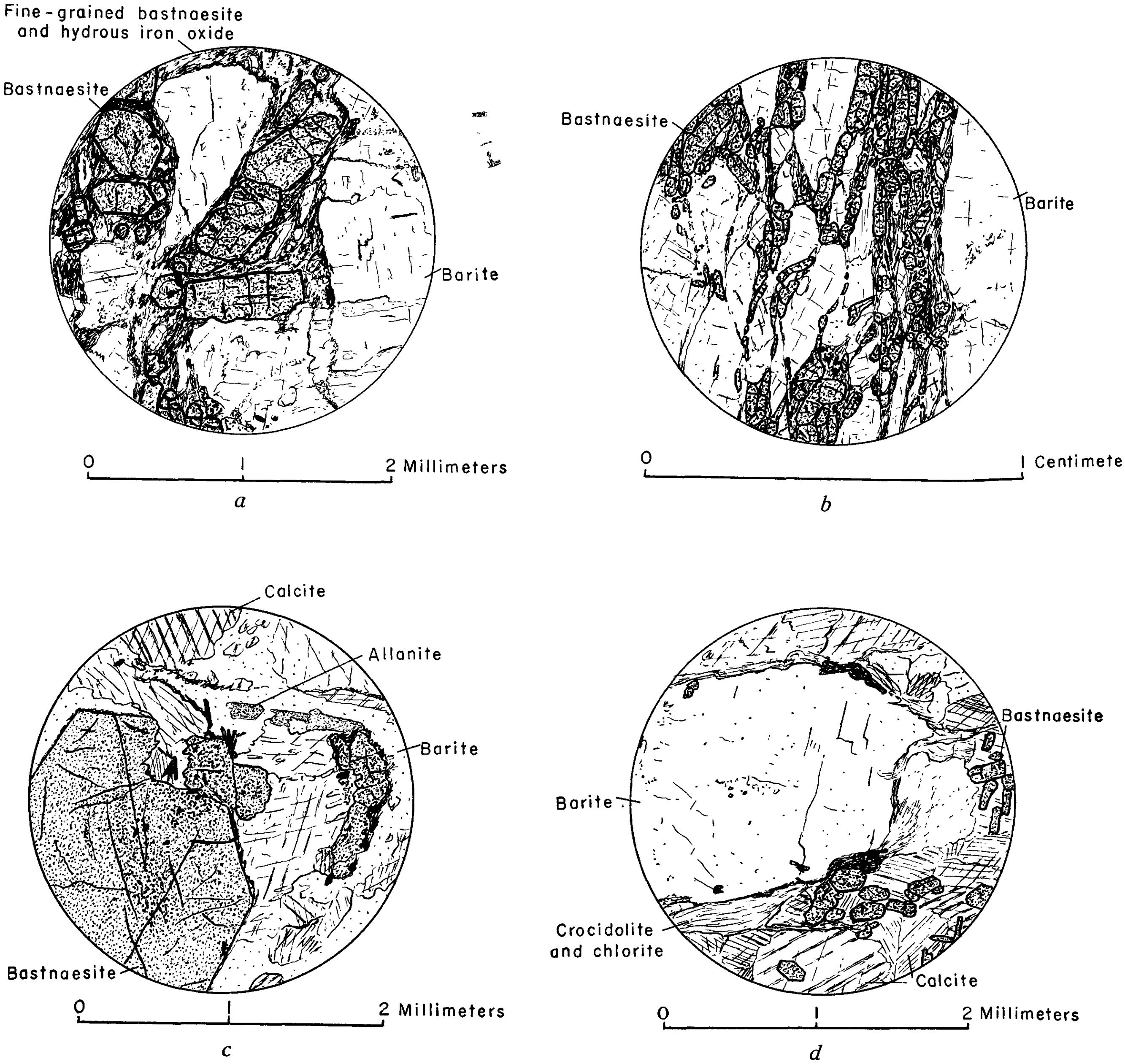

FIGURE 10.—CAMERA LUCIDA DRAWINGS.

a. Sheared barite-bastnaesite rocks. Subhedral to euhedral bastnaesite crystals (high relief) in a matrix of fine-grained bastnaesite and probably hydrous iron oxide interstitial to ragged barite grains (white).

b. Sheared barite-bastnaesite rock, similar to *a*, showing gneissic structure.

c. Broken euhedral bastnaesite crystal (high relief) cemented by calcite, barite, and hematite. Pleochroic allanite occurs in pink barite which forms irregular patches and streaks through calcite.

d. Crocidolite and chlorite in shears around barite crystal in calcite-bastnaesite matrix. Groups of euhedral bastnaesite crystals occur in calcite.

The specific gravity of these rocks ranges from 3.56 to 3.99.

The dense, hard siliceous rock forms relatively resistant outcrops. The southwest end of the carbonate body consists of a dense white barite-rich rock containing bastnaesite, quartz, and some monazite, and it is stained with manganese on weathered surfaces. Similar silicified rocks containing both pink and white barite, and bastnaesite, are found in other parts of the carbonate body, such as along the fault cutting the middle of the body (see pl. 8). These silicified rocks occur mostly in sheared parts of the carbonate mass, and silica has been

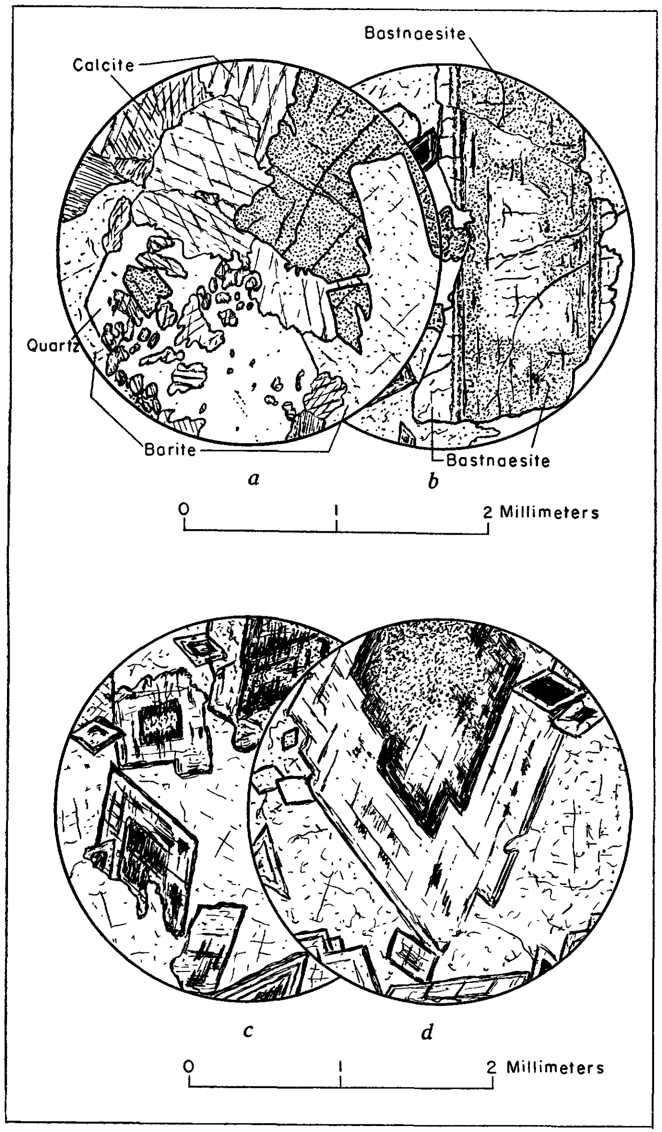

FIGURE 11.—CAMERA LUCIDA DRAWINGS.

a. Post-bastnaesite barite and calcite, replaced by euhedral quartz crystal (lower left), which contains residual blebs of calcite and a subhedral bastnaesite crystal. A crack in the large irregular bastnaesite grain (right center) is filled with calcite and barite; euhedral barite also penetrates the bastnaesite.
b. Zoned bastnaesite crystal. Zoning in bastnaesite is shown by an irregular clear core and alternating zones of bastnaesite with or without many dusty inclusions.
c. Barite replacing iron-stained carbonate rhombs.
d. Barite replacing iron-stained carbonate. Barite penetrates slightly into right edge of the large crystal of rhombic carbonate.

introduced along the shear foliation. Carbonate rock bordering the silicified rocks in many places contains doubly terminated quartz crystals a few millimeters to a centimeter long. The quartz is pink to pale yellowish brown. Some euhedra of yellowish-brown quartz occur

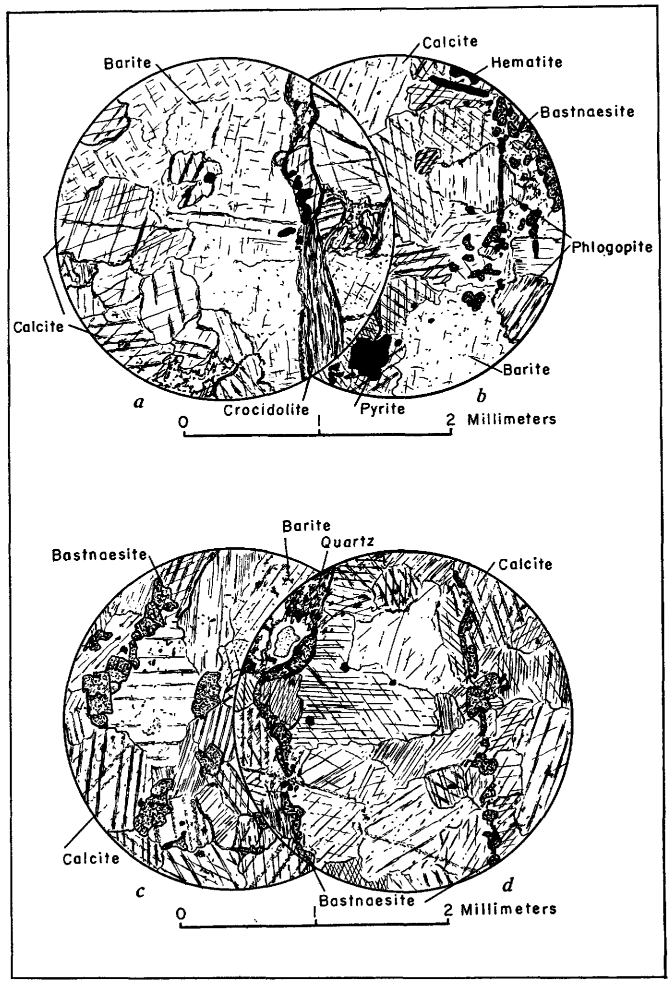

FIGURE 12.—CAMERA LUCIDA DRAWINGS.

a. Crocidolite-filled shear in barite-carbonate rock. Twinned anhedral calcite grains with barite which shows cleavage. The shear in the right half of the view is filled with crocidolite, and galena (opaque) occurs in and near the shear plane.
b. Phlogopite veined by bastnaesite in barite-calcite rock. Anhedral bastnaesite is scattered through the rock and fills a cleavage crack in the phlogopite.
c. Anhedral and subhedral bastnaesite in calcite.
d. Bastnaesite in parallel streaks in calcite. Some hematite grains (dark) are present. Barite is surrounded by clear quartz in an area of dusty iron oxide material at the upper left edge.

in late veinlets of white barite along the shear foliation. Hexagonal plates of bastnaesite occur with random orientation in streaked barite-carbonate rock bordering silicified zones.

The silicified carbonate rock is similar in texture to the gray calcite-pink barite rock, but has abundant quartz and correspondingly lower calcite content. The quartz fills cavities presumably formed by the removal of calcite in solution. Coxcomb structure is typically developed in the quartz, as in figure 13. Three or four

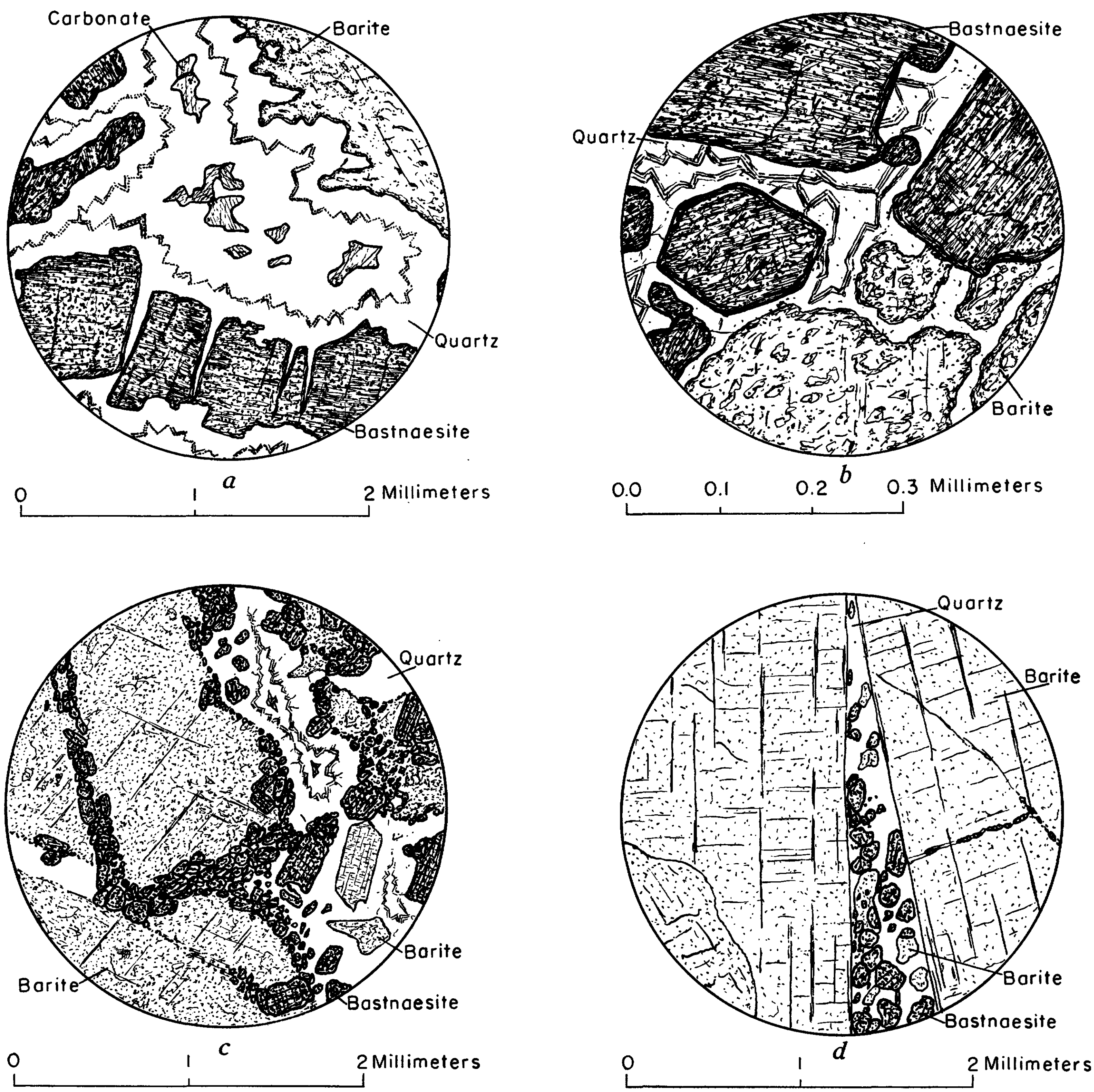

FIGURE 13.—CAMERA LUCIDA DRAWINGS.

a. Quartz lining vugs in barite-bastnaesite rock. Broken bastnaesite crystal is invaded by quartz along cracks. Vugs within the barite-bastnaesite rock have been lined with coxcomb quartz which is coated with additional quartz. Carbonate fills cores of the vugs.

b. Quartz lining vugs in barite-bastnaesite rock. Subhedral to euhedral bastnaesite and ragged barite are cemented by late quartz.

c. Fine-grained bastnaesite in veinlets and fractures in barite. Bastnaesite developed along lines in single barite grain, and at the edges of barite grains. Quartz replaces barite, as at the left edge of the view, and fills vugs between bastnaesite and barite. Carbonate forms the cores of many vugs.

d. Fine-grained bastnaesite in veinlets and fractures in barite. Crack along barite cleavage is filled with rounded grains of bastnaesite and barite which are cemented by quartz.

growth layers are indicated by minute dusty opaque inclusions in the quartz. Some of the quartz is extremely fine-grained and is in colloform structures. Late carbonate fills the cores of many of the quartz-lined vugs (fig. 13). In some thin sections, quartz replaces coarse barite preferentially without affecting the adjacent or surrounding grains of bastnaesite. Residual, uniformly oriented blebs of barite are enclosed in unoriented grains of quartz. Veins of nearly pure quartz a foot or two thick occur in a few places along the fault cutting the carbonate body.

In the silicified carbonate rock, subhedral to euhedral crystals of bastnaesite (fig. 10*a*, *c*, and *d*) are in many places broken (fig. 10*c*) or ground into minute grains (fig. 10*b*). Figure 13*c* shows bastnaesite that has grown in linear disposition in barite. Figure 13*d* shows a single grain of barite which has been wedged apart along cleavage, the fracture being filled with quartz containing rounded barite and bastnaesite. Similar broken barite, cemented by quartz-bastnaesite rock, is seen in outcrops at the southwest tip of the carbonate body. Some of the bastnaesite in the silicified rock occurs as hexagonal plates, such as the broken grain in figure 13*a*, rather than prisms. Sericite replaces bastnaesite locally.

The barite in the silicified carbonate rock, as seen in thin section, displays "patch replacement" features, where untwinned barite transgresses twinned barite of different optical orientation. Bladed or fibrous barite occurs in the silicified rock in late seams lined by quartz and containing euhedral quartz crystals.

A little of the carbonate is a late introduction, possibly redistributed from the carbonate of the main mass. It occurs in the centers of quartz-lined vugs. Needlelike crystals and plumose bunches of carbonate mineral, radiating from bastnaesite, are coated by colloform quartz in which are coarse crystals of the later calcite. Sparse rhombic carbonate similar to that in figure 11*c* and *d*, is partly replaced by barite and calcite.

The silicification is thought to be due to hydrothermal solutions which, after the formation of the carbonate body, dissolved carbonate and minor amounts of barite along shear zones, forming open cavities. Continuing movement along the shear zones may have collapsed this porous rock and thus concentrated the bastnaesite and barite in the shear zones. The later silicification is shown by coxcomb quartz, and calcite was then deposited in the cores of the vugs. The carbonate and barite dissolved and removed in solution may have been redeposited in veins away from the carbonate body.

Allanite is locally abundant, with minor galena and quartz, in late veins of bladed pink strontian barite that cut rock rich in reddish barite, crocidolite, and chlorite, near 4360 S., 555 E. of the map grid.

Aragonite veins occur in all types of carbonate rock in the Sulphide Queen carbonate body (see pl. 8), and are considered to be very late features, possibly supergene in origin.

FOLIATION

The foliation of the carbonate rock is due to the elongation and alinement of barite, fibrous crocidolite and chlorite, and phlogopite, and other minerals in a carbonate matrix. The most apparent and widespread foliation, shown by elongation and alinement of barite grains averaging 1 cm in size, is illustrated in plate 6*B*. Locally, the barite forms elongate oriented lenses in the carbonate matrix. The pronounced development of the alined barite grains adjacent to contacts and around inclusions strongly suggests flowage of the carbonate mass within its enclosing walls. In many places, especially at the east-central edge of the main carbonate body, the streaks of barite are paralleled by minute wavy shears filled with crocidolite and chlorite. In the satellitic carbonate mass east of the north end of the main body, the banding (pl. 6*D*) is apparently due to different proportions of fine-grained ferruginous carbonate, dark minerals, and pink barite in the layers. The even banding illustrated in plate 6*D* is not representative of most of the carbonate rock. Phlogopite flakes are abundant in parts of this rock, and are alined roughly parallel to the layering.

The foliation due to alinement of barite grains, called streaked barite foliation, is generally parallel to contacts, as indicated on plate 4 and figure 14. The foliation in the south and southwest part and especially in the north tip and along the east edge of the carbonate body, conforms to the contacts. The foliation around the large brecciated gneiss inclusion, at 5600 S., 700 E. of the map grid, is conformable with the edge of the inclusion wherever exposed. Streaked barite foliation strikes slightly north of west and dips north in the whole central part of the carbonate body. The irregular western edge of the body shows irregular orientation of the foliation. In a few places, as in the detached carbonate leaf east of the southern part of the carbonate body, the foliation does not conform to the contact, except within a few inches of the contact. Figure 14, which represents a hypothetical adjustment of the carbonate body along the indicated lines of displacement, shows a general concentric distribution of foliation parallel to the postulated original elliptical outline of the body.

Another type of foliation is due to barite in parallel wavy shear planes in the carbonate rock. As shown in plate 4, this foliation transects the streaks of barite

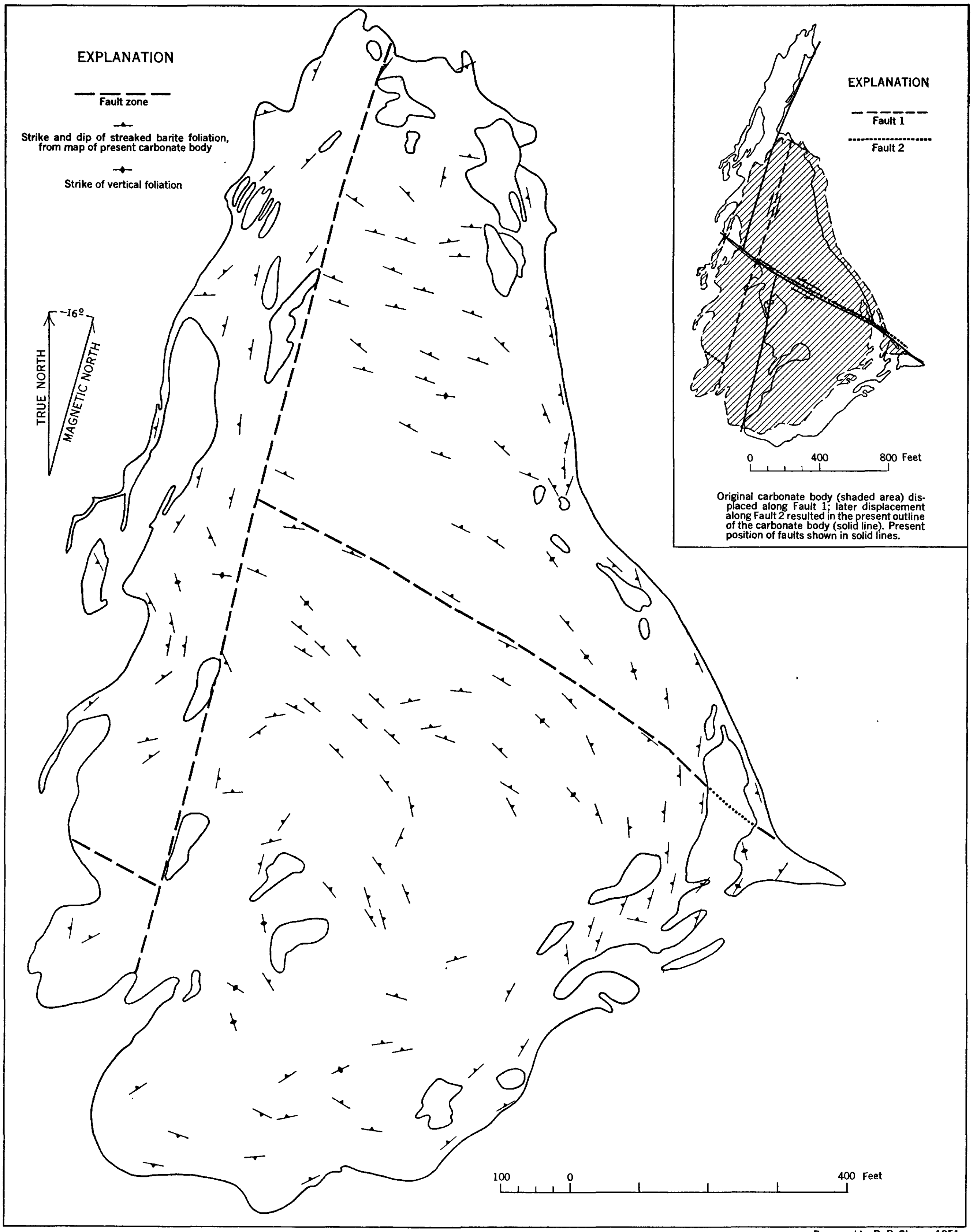

FIGURE 14.—Hypothetical outline of original carbonate body before faulting. Inset map shows present outline and postulated sequence of faulting.

grains, cutting individual barite grains, and hence is later than the barite streaks. The shear foliation is best developed in the southern part of the main carbonate body. In general it is parallel to shear planes in and adjacent to the carbonate rock, some of which displace the carbonate body. Hence it was developed after the emplacement of the carbonate rock and suggests a redistribution of barite in the rock. The barite shear foliation is in many places parallel to crocidolite and chlorite in wavy shear planes which either cut or are parallel to the streaked barite foliation. Thus the barite and the crocidolite-chlorite shear foliations are probably essentially contemporaneous.

INCLUSIONS

The distribution of inclusions in the carbonate body is shown on plate 4, and the peripheral disposition is apparent in figure 14 which shows the hypothetical original outline of the carbonate mass. The inclusions range from breccia fragments a fraction of an inch in diameter to bodies 150 feet long. Some inclusions a few feet long are unbroken and surrounded by carbonate rock which shows flow foliation adjacent and parallel to the boundaries of the inclusions. Other large masses, such as the gneiss block at the south end of the carbonate body at 5600 S., 700 E. of the map grid, are thoroughly brecciated and penetrated by carbonate rock but are surrounded by similarly foliated carbonate rock. Examples of carbonate penetration of inclusions are shown in figures 15 and 16. Some of the large gneiss inclusions in the carbonate body, such as those at 5400 S., 500 E.

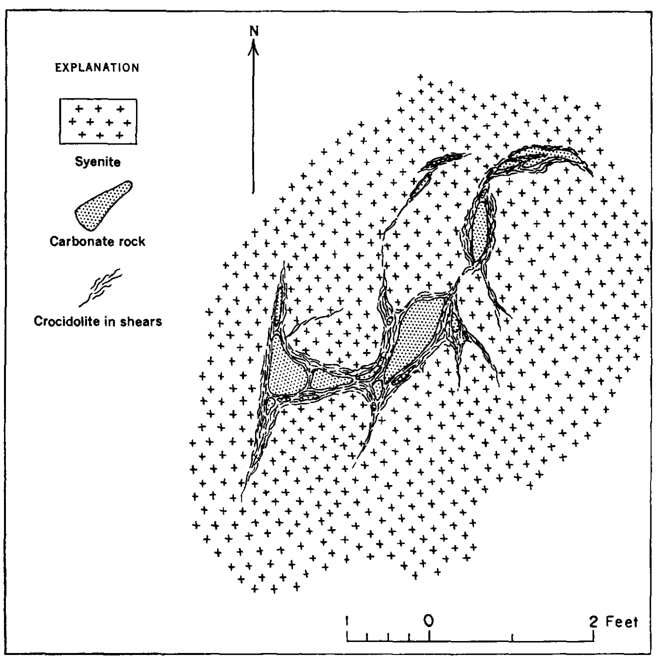

FIGURE 15.—Irregular carbonate pods in syenite inclusion in Sulphide Queen carbonate body.

FIGURE 16.—Carbonate pod in gneiss inclusion in Sulphide Queen carbonate body.

and 5600 S., 700 E. of the map grid, are more brecciated than the leaves of gneiss that extend into the carbonate body from the walls. The proximity of the inclusions to the walls suggests that the inclusions are detached leaves that have been rolled in the carbonate rock during the flowage of that mass.

Most of the syenite inclusions are in the northern half of the carbonate mass. No syenite occurs in the wall rock adjacent to the carbonate body, except small bodies such as the one at 5280 S., 1175 E. of the map grid (pl. 4). The large syenite inclusion at 4100 S., 550 E. probably touches the gneiss wall rock; however, the absence of syenite in the wall rock indicates that the syenite inclusions may have moved some distance from their original position in the gneiss. There is little evidence of replacement of the borders of the inclusions by carbonate material, an indication that the carbonate rock did not form by replacement of a breccia zone.

Except for the large shonkinite-syenite inclusion in the north end of the carbonate mass, the only shonkinite inclusions are small bodies or fragments in breccia. Although large masses of granite occur within 300 feet of the north end of the carbonate body, no granite inclusions have been found in the carbonate rock.

SHEAR ZONES NEAR THE SULPHIDE QUEEN CARBONATE BODY

The braided shear zones (pl. 9) strike northwest, in places coinciding with the foliation but generally more westerly. The resulting shear pattern is a braided one controlled in part by the pre-existing gneiss foliation. All the major shears mapped in this area dip steeply southwest except the one along which a large fine-grained shonkinite dike, on the northeast side, is offset 750 feet southeast; this shear zone dips steeply northeast. A second fine-grained shonkinite dike, northwest of the north end of the main carbonate mass, is abruptly terminated to the northeast by a major shear zone. The dike, about 5 feet wide at this point, and a dike extending from the east side of the carbonate body, were not found on the other side of the shear, within the mapped area; hence the displacement on this fault may exceed 1,000 feet.

On several of the shear zones (pl. 9) the northeast side apparently moved southeastward. The surface outline of the Sulphide Queen body suggests that the northeast side moved northwestward along the shear that cuts the middle of the carbonate mass. Since the carbonate mass dips west at a low to moderate angle, the present relationship could be obtained by movement along this fault opposite to the apparent direction, but at a steeper angle than the local attitude of the carbonate body. The attitudes of slickensides in the different shear zones in the area are varied, as shown in plate 4, and do not correspond with the apparent direction of movement shown by displacement of contacts.

Zones of carbonate rock breccia occur in the carbonate body. The most conspicuous zone, striking slightly east of north, is exposed along the bottom of a gully in the northern part of the carbonate body. The east contact of the carbonate body near the north end is in line with the breccia zone. In the carbonate mass the zone forms a line across which are abrupt changes in the attitudes of the minor structural features of the rock (see pl. 4). This zone appears to be one of appreciable displacement. If the movement along the zone had been such as to displace the north tip of the carbonate body northward, and adjustment is made for displacement along the middle fault, the original outline may have been more nearly as indicated in figure 14. This postulated movement would also bring into approximate alinement the similar granite bodies north and east of the north end of the carbonate mass.

One of the southwest-dipping major shear zones cuts the middle of the carbonate body and one truncates the north tip; a third fault of this set, or possibly an unrelated fault, may truncate the south end of the body, but is not exposed.

ALTERATION OF WALL ROCKS

Contacts between the Sulphide Queen carbonate body and older rocks are sharp, but the igneous rocks and gneiss are altered. Crocidolite- and chlorite-filled shear planes are abundant along and near the contacts. Carbonate rock locally penetrates other rocks as a web of ramifying veinlets. Irregular blebs of carbonate rock, showing streaks of barite parallel to contacts, occur locally in the gneiss wall rock and in large inclusions of wall rock near the edge of the carbonate body. Two examples are illustrated in figures 15 and 16, drawn from outcrops of large inclusions at 4715 S., 780 E. and 4945 S., 890 E., respectively, of the map grid (pl 4).

Gneiss and syenite near contacts with carbonate rock are commonly reddened by hematite in blebs, veinlets, and dusty forms. Feldspars are pinkish gray in color because of disseminated fine hematite dust, part of which is probably weathered to goethite. The extent and distribution of the alteration around carbonate rock is shown in plate 9. The outward extension of the alteration around the south end of the carbonate body suggests that carbonate rock is near the surface west of this part of the body, implying a shallow west dip of the contact. The fragments of syenite and gneiss in the carbonate rock invariably are bordered by rims 1 to about 25 mm thick in which the feldspathic rock is rich in phlogopitic biotite, resembling shonkinite. The mica in thin section shows low refractive indices and pale colors in green and brown. One phlogopite from a dark selvage around a syenite fragment in carbonate rock at 3660 S., 740 E. of the map grid, plate 4, is pale greenish-brown and has a refractive index for nY and nZ of approximately 1.58; it has abundant acicular inclusions along crystallographic directions.

Granitic gneisses near the contacts have been altered to aggregates of coarse-grained, pinkish-gray feldspar, such as the gneiss illustrated in plate 9, which locally contains pegmatitic blebs of biotite and feldspar. Garnet porphyroblasts in these gneisses are replaced by aggregates of phlogopite, with probably some chlorite and crocidolite.

It is suggested that much of the dark, mica-rich rock in inclusions within the main carbonate mass has developed by the reaction of carbonate rock with gneiss and syenite. The development of phlogopite from orthoclase requires magnesia, which is present in the carbonate rock, and water. Variation in iron content of the micas is readily explained by original local variation in the contact rocks. That phlogopite also develops through the alteration of garnet implies the stability of phlogopite under the conditions of metamorphism. Some of the syenite apparently has formed by replacement of gneiss. The relative increase of potash feldspar locally in the contact zone may have been a result of a real increase in the constituents of that mineral, or of a decrease in silica possibly by the removal of quartz.

CARBONATE ROCKS IN THE AREA BETWEEN THE SULPHIDE QUEEN AND BIRTHDAY SHAFTS

Between the Birthday and Sulphide Queen areas, the carbonate rock occurs predominantly in thin tabular bodies from an inch to about 20 feet in width, corresponding in attitude generally with the northwest and northeast sets of igneous dike rocks. The bodies about half a foot or less in width are not indicated on the geologic map (pl. 4). A podlike body just north of the northern end of the main carbonate mass is about 100 feet long and 60 feet wide. Carbonate rock occurs as small ramifying dikes and pods in much of the brecciated zones. It also cuts the igneous rocks in anastamosing veins a fraction of an inch to several inches thick, especially in the shear zones.

Although little petrographic study has been made of the carbonate rocks in this intervening area, the rock varieties can be compared with similar studied types in the Birthday and Sulphide Queen areas. The carbonate rocks in this area are largely gray calcite and dolomite which contain grains of pink strontian barite and in places white barite commonly about 1 cm in diameter, with smaller amounts of finer grained bastnaesite. The darker brown weathered surfaces of other similar carbonate veins in the area suggest the presence of more ankerite and siderite. Bastnaesite is scattered in these rocks, and allanite occurs in a few. Monazite has been found in 1-inch veinlets, composed chiefly of brown carbonate and pink barite, just north of the Sulphide Queen carbonate mass. Where carbonate veins are cut by shear zones they commonly have been silicified to a dense, yellowish to dark brown rock, containing varying amounts of white or pink strontian barite, similar to the silicified bastnaesite-rich types in the main Sulphide Queen mass.

North of the Sulphide Queen carbonate body, radioactivity due to thorite was noted in several veins, particularly where shearing and hematitic staining is apparent. The maximum radioactivity observed in this area is 1.3 mr per hour. Among the more radioactive veins are the Birthday discovery vein near 1250 S., 230 W. and the vein near 1240 S., 500 W. on the map grid (pl. 4). Many other carbonate veins in the Birthday-Sulphide Queen area have abnormal but generally lower radioactivity. The shear zones at 2575 S., 850 W. and 2780 S., 50 E. of the grid (pl. 4) show radioactivities of 0.20 and 0.15 mr per hour, respectively. The large granite body east of the north tip of the carbonate body shows radioactivity of 0.15 mr per hour, and the shear zone between this granite body and the north tip of the carbonate body 0.15 mr per hour.

CARBONATE VEINS IN THE BIRTHDAY AREA

RELATION OF VEINS TO COUNTRY ROCK

The carbonate veins in the Birthday area (see pls. 10 and 11; also Sharp and Pray, 1952) occur in the large mass of shonkinitic rock and in the contact zone in the enclosing metamorphic complex. This complex consists largely of granitic augen gneiss, with lesser amounts of quartz-biotite schist, quartz-sericite schist, and minor hornblende gneisses and schists. The foliation of the metamorphic rocks in this area strikes from north to N. 80° W., and the dip ranges from 30° to 70° southwest. Most observed attitudes conform to the regional trend of N. 20°–40° W., and dip about 50° SW.

The Birthday area is in the northwestern part of the largest of the intrusive bodies, the shonkinite that crops out in an area about 6,300 feet long and 1,500 feet wide. The margins of the shonkinite converge and are less regular toward the northwest, and the northwest end of the body is only a few hundred feet west of the mapped area (pl. 10). Most of the contacts in this area are poorly exposed, and it is possible that the contact is locally faulted, as northeast of the Birthday shaft. The shonkinite in the Birthday area is cut by many thin syenite, granite, and fine-grained shonkinite dikes, and by carbonate veins.

The dikes and the veins in the Birthday area trend in many directions, but commonly in two. One trends west to about N. 60° W., and dips southward at moderate to steep angles. The other trends generally northeast and dips to the northwest at moderate to steep angles. The first is the better developed, as shown, for example, by many thin dikes and veins in the southeast part of the Birthday area. In the central part of the area, this trend shifts more westerly, and in the northwestern part, where fewer veins and dikes are present, the prevailing trend is slightly north of west. This general set of features appears to be roughly parallel to the outlines of the shonkinite body, and thus they appear to occupy longitudinal fractures. Locally some of the carbonate veins, especially those of ankerite, appear to be along east-west shear planes. At other places, the highly irregular and jagged shape of the carbonate veins suggests the openings were tensional fractures.

The second preferred orientation of dikes and veins is less well defined, and trends about N. 20°–60° E. with the principal exception of the large late shonkinitic dike, which dips steeply to the south, the veins and dikes along this trend appear to dip northward at moderate to steep angles. Shear planes parallel to the northeast trend have not been observed. In the Birthday area, the major representatives of this northeast trend (locations on pls. 4 and 10) are: the large fine-grained shonkinite dike (1600 S., 950 W.); the large granite dike at 2000 S., 875 W.; granite dikes and carbonate veins north of the Birthday shaft, some of which contain bastnaesite and one of which extends into the gneiss along ths trend; and small granite dikes and apophyses of larger bodies east of the Birthday shaft.

There is little evidence within the Birthday area of major faulting or folding after intrusion of the shonkinite, although the contact between shonkinite and gneiss northeast of the discovery shaft may be a fault contact. However, the rocks are broken along many joints, shear planes, and small faults. Most of these fractures strike northwest and dip 30°–60° NE. At most places where displacement can be observed, the northeast side has shifted southeastward relative to the opposite block.

Contacts between the veins and the enclosing rock in the Birthday area are generally sharply defined. Locally the shonkinite adjacent to the veins is extensively altered, particularly near the major ankeritic veins, which appear to have formed by the progressive replacement of the shonkinite or syenite along a host of subparallel fractures. In this replacement the augite and biotite alter largely to chlorite, carbonate minerals, sericite, and iron oxides. Serpentine has been locally identified as an alteration product. The microcline does not appear to be readily decomposed, but is replaced by sericite, and by a carbonate mineral, probably ankerite, along many fractures. This replacement by carbonate minerals appears to follow east-west shear planes in much of the area, and where it has been the most extensive, large ankeritic veins have been formed. A few slabs and lenses of altered shonkinite within these ankeritic veins are recognizable by the relict shonkinite texture. Some of the veins appear to be localized by the granite or fine-grained shonkinite dikes.

Most of the veins in the Birthday area are but a few feet thick; the maximum thickness observed is 18 feet. Several veins from 5 to 8 feet in thickness can be traced as lenticular bodies for more than 100 feet along the strike; most of the veins are less than 5 feet thick and are 50 to 100 feet long. One vein that is nowhere more than 3 feet in exposed thickness is more than 500 feet long.

CLASSIFICATION OF THE BIRTHDAY VEINS

The veins of the Birthday area are not uniform in composition, but show marked mineral variation even at different points within the same vein. Despite the variation, certain mineral assemblages occur commonly, and can be used to classify and, thereby, conveniently describe these veins. On the basis of the major minerals, the veins are divided into calcite-barite-bastnaesite veins; calcite-barite veins; siderite-barite-bastnaesite-quartz veins; ankerite-barite veins; ankerite-fluorite veins; and quartz veins.

Veins composed largely of calcite and barite with or without appreciable amounts of bastnaesite are the most abundant type in the Birthday area. Probably more than half of the bastnaesite occurs in veins composed largely of calcite, with lesser amounts of bastnaesite and barite. Light-gray calcite forms as much as 90 percent of these veins, and occurs in crystals generally a few millimeters in size. Light-tan to pink barite is almost invariably present in amounts ranging from 5 to 30 percent of the rock. Bastnaesite occurs in tabular crystals that range in length from as much as 4 to less than 0.1 inch (see pl. 6*C*). Locally the bastnaesite content across the width of a vein may be as high as 30 percent, but the average content of even the richer veins is probably not more than half this amount. Minor minerals identified in the calcite-barite-bastnaesite veins include siderite, quartz, fluorite, galena, pyrite, apatite, crocidolite, and wulfenite.

Bastnaesite is either absent or is only a minor mineral in many calcite-barite veins. Most veins of the Birthday area, and nearly all of the Birthday veins south of the late shonkinitic dike, are of this calcite-barite type. The contacts of the calcite-barite veins with the shonkinite are generally sharp, and the wall rock does not appear to have been altered along these veins. The veins generally are less than 2 feet thick, but locally appear to be as wide as 5 feet. Veins of the calcite-barite class are more persistent laterally than other types of carbonate veins, and one vein appears to be about 500 feet long, although it is generally only 1 to 3 feet wide. Some of the calcite-barite veins have a mineral banding parallel to the walls, which may have formed by mineralization along repeated fracture or shear planes, or possibly as a primary foliation formed by movement during crystallization.

The original discovery and much of the subsequent prospecting in the Birthday area has been in siderite-barite-bastnaesite-quartz veins found in the area of the discovery shaft. In these veins, siderite is the dominant carbonate mineral and locally forms more than half of the vein. Ankerite and calcite are minor carbonate minerals. Barite and bastnaesite form a third or less of the veins, and quartz is less abundant. The abundant goethite in these veins is believed to be largely derived through weathering of siderite, although some probably has been derived from pyrite. The bastnaesite and siderite appear to be early minerals and are cut by later barite, calcite, and quartz. At the discovery shaft, the veins of this type are as thick as 7 feet, but the average thickness is about 3 or 4 feet. Locally bastnaesite forms nearly half of these veins, but the average content of bastnaesite is much less. Closely associated with the bastnaesite-rich veins at this locality are veins of carbonate minerals and barite that appear to be replacing the shonkinite along a series of east-west shear planes. In the area near 1540 S., 1130 W. (pls. 4 and 10), veins of siderite, barite, and bastnaesite grade laterally into veins composed largely of calcite, barite, and bastnaesite. There appear to be complete gradations between these vein types.

Veins composed largely of ankerite and barite are not common in the Birthday area, but the thickest vein is of this type. This large vein, near 1450 S., 800 W., has a maximum thickness of 18 feet. It is composed largely of pale cream-colored ankerite, and contains a third or more of barite and barian celestite, in crystals as large as an inch. Bastnaesite is apparently absent from this large vein, but a few crystals of it occur in a smaller vein of this type near 1220 S., 1470 W. Quartz is a common but minor mineral. Purple fluorite is conspicuous and is confined largely to thin fractures in the earlier veins. Fluorite, galena, and oxidized copper minerals probably form less than 1 percent of the veins.

The veins of the ankerite-barite type are generally lenticular. The one with a thickness of 18 feet thins and splits into several veinlets less than 1 foot thick in a distance of about 100 feet. Shonkinite adjacent to this type of vein commonly is highly altered and cut by many small carbonate veinlets. Within the vein, small bodies of altered and partially replaced shonkinite can be recognized locally. These veins appear to have formed by progressive replacement of shonkinite by hydrothermal solutions that penetrated and spread outward from innumerable closely spaced shear zones in the shonkinite.

Ankerite-fluorite veins are abundant in the Birthday area, but are of minor quantitative significance. These veins range in thickness from a fraction of an inch to 6 inches and are composed entirely of ankerite, or of ankerite with a few percent of purple fluorite. The ankerite is coarsely crystalline, and cleavage surfaces commonly extend across the entire width of the vein. Several of these veins cut the large fine-grained shonkinite dike as at 1600 S., 960 W. The north strike and moderate east dip of some of these veins does not parallel most other veins of the area. These veins probably are related to the other veins of the area, but possibly are distinctly later than the bastnaesite-bearing veins or the larger and more complex ankerite-barite veins. Carbonate veins in which ankerite is an important constituent do not appear to contain significant amounts of bastnaesite in the Birthday area.

In the northwestern part of the map area (pls. 4 and 10), several fine-grained quartz veins form conspicuous outcrops. The observed veins range in thickness from less than a foot to 10 feet. Most strike west to northwest and dip steeply to the south. These veins occur in the shonkinite and the gneiss. Some were brecciated during formation and the fractures have been recemented by silica. Near 1800 W., 1400 S., one quartz vein cuts across a bastnaesite-bearing vein and another occurs along a thin carbonate vein, and appears to replace it. The quartz veins probably are younger than the carbonate veins, but they could be of about the same age.

SULPHIDE QUEEN GOLD MINE

The old Sulphide Queen gold mine consists of an inclined shaft about 320 feet deep and about 2,200 feet of drifts on four levels (pl. 12). These workings explore a northwest-trending shear zone dipping steeply southwest. Granite forms the hanging wall in most of the workings, and gneiss with a little shonkinite the footwall. The shear zone was explored mainly for gold. Stringers of quartz, calcite, and abundant iron and manganese oxides occur along the shear planes. The radioactivity in the mine, which is several times surface background, is apparently due to thorium-bearing minerals which are associated with iron and manganese oxides in sheared, chloritized rock. Several thin carbonate veins are also exposed by the workings, and these contain rare earths, probably as bastnaesite. The tailings pond about 300 feet east of the Sulphide Queen gold mine (pl. 1) is radioactive from 0.15 to 0.20 mr per hour.

WINDY GROUP OF PROSPECTS

The mineralized shear zone in the Windy group of prospects was mapped in a strip about 2,000 feet long averaging 300 feet wide (pl. 13). The shear zone cuts interlayered laminated granitic gneiss, granitic augen gneiss, chloritized mafic augen gneiss, quartz-hornblende-plagioclase gneiss, and schists. The schists are gradational in texture to the chloritized mafic augen gneiss. The gneisses crop out, while the schists are more deeply weathered and are obscured by float from the outcrops. Blank areas on the map (pl. 13) are probably underlain largely by schist or easily weathered gneiss such as the chloritized mafic augen gneiss.

Shonkinite is found as lenses in the shear zone, associated with thorium-bearing carbonate rock. In places, such as illustrated in figure 17 and near 350 S., 350 E., the vein contains fragments of shonkinite and altered gneiss with crocidolite and phlogopite. In places, carbonate-barite vein material is disseminated in the shonkinite and the contact is apparently gradational between the shonkinite and the vein.

Well-defined tabular veins occur in the shear zone, as near 100 N., 00 (pl. 13), and in irregular forms as at 425 S., 400 E., and at 900 S., 750 E. (fig. 17). The veins consist of abundant hematite, goethite, carbonates, barite, quartz, some thorite, and minor bastnaesite. Near 425 S., 500 E., fluorite is abundant in a silicified carbonate vein showing low radioactivity.

The northernmost vein on the Windy prospects is exposed in the Windy No. 1 pit, which is 8 feet deep, at 130 N., 20 W. (pl. 13). The vein is 300 feet long, and at the pit it is 4 feet thick. Locally the vein is brecciated, for example at a pit at 110 N., 00. The vein here is 4 feet wide, contains many fragments of shonkinite and gneiss, and occurs between brecciated gneiss on the east wall of the vein and a lens of shonkinite which forms the west wall.

Within 25 feet north of the thick andesitic dike which cuts the vein at the north end of the Windy prospects, the vein has high radioactivity in two places (1.2 mr per hour). Just south of the dike, in the No. 1 pit, the radioactivity of the vein is 1.2 to 1.5 mr per hour. The walls within 2 feet of the vein here are radioactive to as much as 0.20 mr per hour. Radioactivity of the vein at 110 N., 00 ranges from 3.5 to 4.5 mr per hour. The gneiss in the east wall here has radioactivity of 1.1 and shonkinite in the west wall has radioactivity of 0.7 mr per hour. Beyond 3 feet from the vein the radioactivity of the wall rock is that of average gneiss.

The small vein near 200 S., 200 E. is abnormally radioactive (6.0 mr per hour) 50 feet north of the andesitic dike. A set of parallel closely spaced veins 100 feet south of this dike has radioactivity as high as 1.1 mr per hour. Comparable radioactivity is found farther south in veins near the small dikes at 800 S., 700 E. on the map grid (pl. 13). The small parallel closely spaced veins 300 feet southeast of these dikes show a maximum radioactivity of 1.5 mr per hour, and no andesitic dike is exposed near them.

RAY-WELCH-WILLMORE GROUP OF PROSPECTS

The Ray-Welch-Willmore group of prospects (pl. 13) was mapped in a strip 3,200 feet long and 250 feet in average width. Pre-Cambrian metamorphic rocks exposed in the area consist of hornblende and pyroxene-bearing gneisses, felsic and chloritic augen gneisses, chloritized hornblende schists, laminated granitic gneiss, and pegmatitic granitic gneiss. These rocks are cut by a shear zone in which carbonate rocks containing thorium and rare earths have been introduced. Along a mineralized part of the shear zone shonkinite is found

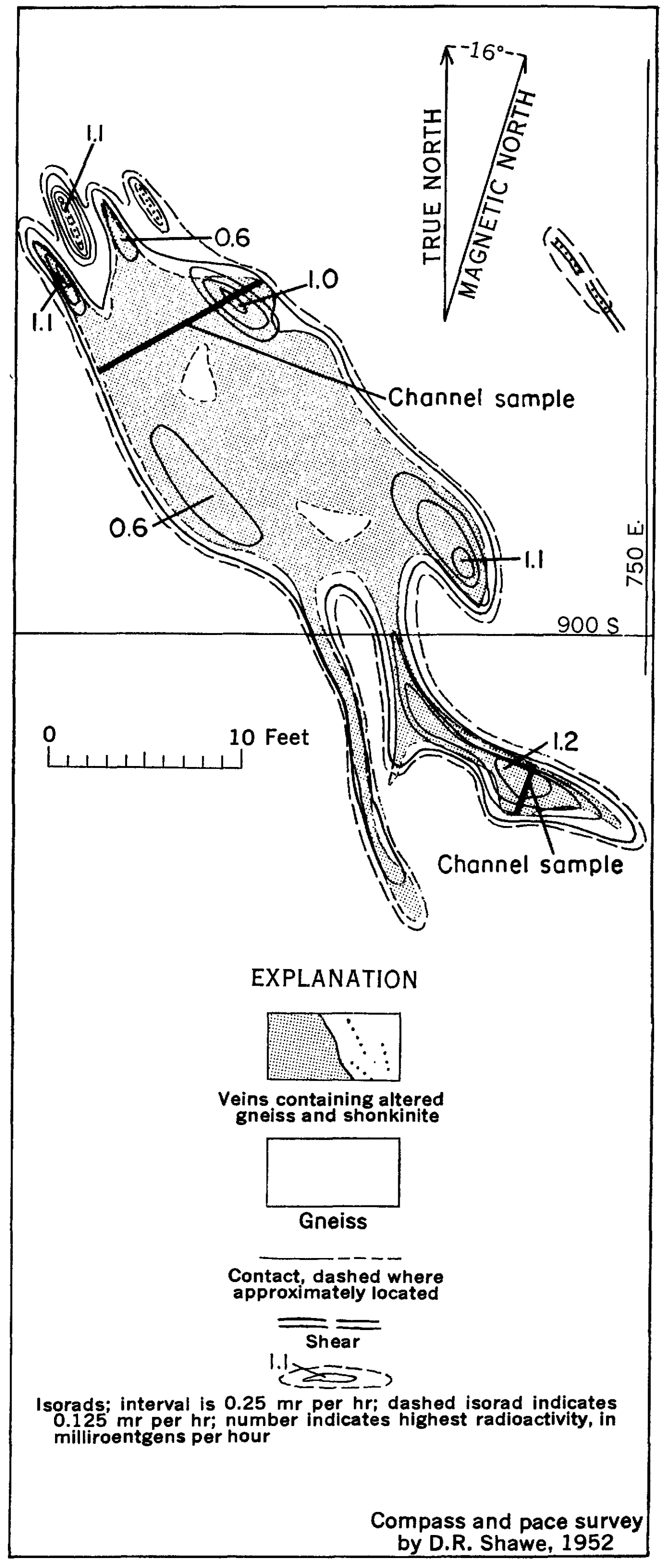

FIGURE 17.—Isorad map of vein at Windy prospects.

near 1200 S., 600 E. on the map grid of the Ray-Welch-Willmore group of prospects (pl. 13). Altered gneiss containing crocidolite and abundant phlogopite occurs near 150 S., 175 W. and near 975 S., 500 E. on the map grid.

The shear zone contains hematite, quartz, goethite, thorite, barite, bastnaesite, and carbonates. Where these minerals are disseminated in the shear zone, the radioactivity is low; higher radioactivity is commonly associated with well-defined thorium- and rare-earth-bearing carbonate-barite veins. Such veins occur near 300 S., 100 W.; 950 S., 500 E.; 1400 S., 675 E.; 2300 S., 850 E.; and 2650 S., 975 E. on the map grid of the Ray-Welch-Willmore group of claims (pl. 13).

Several andesitic dikes, striking generally west, cut the shear zone. One dike, near 250 S., 60 W. on the map grid, intersects but does not cross the shear zone. The dike at 1350 S., 675 E. on the map grid bends where its crosses the shear zone, and since it is apparently not sheared at that point, it is inferred that the shear zone influenced the emplacement of the dike. A chemical analysis of basalt from 800 S., 265 E. on the map grid of the Ray-Welch-Willmore group of prospects (pl. 13) is shown in table 4.

Radioactivity of the deposits in the Ray-Welch-Willmore group of prospects is shown in plate 13. The highest radioactivity is near the andesitic dikes. The pit at 310 S., 100 W. exposes mineralized gneiss with abnormal radioactivity. On the east side of the pit a breccia vein as much as a foot wide contains many gneiss fragments. West of the breccia vein, in the pit, the gneiss in a zone 5 feet thick is fractured and has thin coatings of reddish vein material in the fractures. Radioactivity of the breccia vein in the pit ranges from 0.9 to 1.3 mr per hour and the mineralized gneiss averages about 0.6 mr per hour. Radioactivity 10 feet south and 50 feet north of the pit is less than 0.2 mr per hour, and within 5 feet east and west of the pit radioactivity is normal for the gneiss.

Thorium-bearing minerals are disseminated in the shear zone near 2160 S., 810 E. on the map grid, across 8 feet of reddish-brown, altered gneiss and 3 feet of yellow-brown, altered, intensely sheared gneiss. Radioactivity of the reddish-brown and yellow-brown gneiss averages 0.5 mr per hour. Radioactivity 30 feet north of this point is negligible. To the south radioactivity diminishes and then increases to another high at 2230 S., 820 E. on the map grid, where the shear zone is exposed in a prospect pit. At the west end of the pit is a manganese oxide-stained shear plane dipping about 60° W., east of which is an 8-foot width of red-brown stained, chloritized gneiss, then a 6-inch zone of strongly sheared, red gneiss, east of which is about 6 feet of yellow-brown and red-brown sheared gneiss. Radioactivity of the chloritized gneiss increases from 0.35 mr per hour at the west end of the pit to 0.9 mr per hour at the sheared and reddened zone, in which radioactivity ranges from 0.4 to 1.5 mr per hour. In the yellow-brown and red-brown sheared gneiss east of this, radioactivity is as much as 0.25 mr per hour. Radioactivity is normal a few feet east and west of the pit.

A cut 100 feet south of the pit just described exposes a sheared thorium-bearing carbonate vein about a foot thick, on both sides of which is intensely sheared and altered gneiss. Radioactivity of the thorium-bearing vein is as much as 1.9 mr per hour, and the sheared, altered gneiss on either side is less radioactive. Radioactivity diminishes to about 0.2 mr per hour in chloritized gneiss 10 feet west and 5 feet east of the carbonate vein. Farther west and east the radioactivity is normal.

GOULDER GOULCH PROSPECT

At the Goulder Goulch prospect (location shown in fig. 9), radioactive veins are exposed in six pits and trenches (see pl. 13). The veins are in sheared and altered gneiss which contains abundant goethite and clay (?) minerals. Mafic gneiss is cut by pegmatitic granite gneiss just south of the veins. West and north of the veins are faults striking about N. 25° W., and west, respectively; both faults are expressed topographically by canyons. The west-striking cross fault offsets the shear zone in which the thorium deposits are found (fig. 9).

The veins consist of carbonate material, some barite, quartz, and abundant hematite and goethite. Masses of radioactive material, crowded with fine-grained hematite, are probably thorite. Skeletons of older minerals that have been replaced by dusty aggregates or parallel streaks of hematite and goethite are seen in thin section. Some veins contain fragments of gneiss in which the quartz and microcline, as seen in thin section, are broken and milled. The gneiss has been replaced by carbonate, hematite, thorite (?), and late quartz containing minute needles that probably are rutile. Radioactivity of the veins is as much as 4.0 mr per hour.

REYNOLDS ROBBINS PROSPECTS

The Reynolds Robbins prospect north of Highway 91 (A in fig. 9) consists of two silicified carbonate veins containing rare earths and some thorium. The west vein is about 30 feet long and 4 feet wide in outcrop, but pinches out at each end. It strikes north and dips about 60° W. A shear zone that contains small lenses of shonkinite is exposed in a pit 7 feet deep on the vein. The east vein is 80 feet long, 2 feet in maximum width, strikes N. 20° W, and dips 70° W. Radioactivity of the west vein is 2 to 3 times background, and radioactivity of the east vein does not exceed twice background.

The Reynolds Robbins prospect pit at B in figure 9 exposes red altered gneiss in a shear zone in which is a small lens of shonkinite. This altered gneiss has maximum radioactivity of about 0.6 mr per hour. Radioactivity becomes negligible within 100 feet south along the shear zone, and ranges from 0.1 to 0.15 mr per hour northward along the shear zone 100 feet to a pit where radioactivity is about 0.2 mr per hour. Within 50 feet north of the pit the radioactivity drops to that of the average gneiss.

The Reynolds Robbins prospect pit at C (fig. 9) is 4 to 7 feet deep and 15 feet long, across a mineralized north-striking shear zone in the pre-Cambrian gneisses. In the pit the shear planes dip 72°–80° W., and some of them are mineralized. From west to east the mineralized zone exposed in the pit consists of 3 feet of crushed gray gneiss (radioactivity 0.1 mr per hour); then 3 feet of red-brown stained gneiss (0.2 mr per hour) separated from the gray gneiss by a shear plane; an inch-thick reddish vein (1.2 mr per hour) in a shear plane; 2.5 feet of thoroughly sheared and altered gneiss (0.5 mr per hour); a pronounced shear zone 2.5 feet thick (0.7 mr per hour); 3.5 feet of mineralized gneiss (1.2 to 2.0 mr per hour); and 6 inches of clayey gouge (0.5 mr per hour) at the east end of the pit. The radioactivity diminishes to background 3 feet east of the pit and along the strike of the shear zone 50 feet north and 100 feet south of the pit.

At the Reynolds Robbins prospect D (fig. 9), a carbonate vein in altered gneiss is exposed for about 170 feet along its strike in a shaft and three pits. The southernmost, or third, pit and about 90 feet of the vein are just south of the area shown on the map (fig. 18). Shonkinite is found in two places along the vein, and the vein has been sheared by recurrent movement along the fracture in which it was emplaced. The vein pinches out to the south and is hidden by a dry wash to the north. The radioactivity is indicated on the map (fig. 18).

UNNAMED PROSPECT NO. 3

At the unnamed prospect No. 3 (fig. 9), two andesitic dikes cut the north-trending shear zone in the gneisses on the west side of a canyon. In the sheared gneisses near both dikes, radioactivity of stained joint and shear surfaces is as high as 0.7 mr per hour. The radioactivity is probably due to thorite, associated with hematite which imparts a reddish purple color to the joint and shear surfaces. Average radioactivity across the shear zone 10 feet wide, in the area between the andesitic dikes, is probably no more than 0.1 mr per hour.

Another andesitic dike is about 100 feet south of the unnamed prospect pit No. 3. Where this dike crosses the shear zone shown on figure 9, the radioactivity is locally as high as 0.15 mr per hour.

UNNAMED PROSPECT NO. 4

The vein at the unnamed prospect No. 4 (fig. 9) strikes about N. 40° W. in a shear zone in granitic gneiss and chloritized augen gneiss. The vein, as exposed in a small pit on the north side of the gully which crosses the vein, ranges in width from a fraction of an inch, where it fills a fracture in the gneiss, to a few feet where the vein material is disseminated in gneiss.

Two thin sections of radioactive rock from the vein show rounded grains of quartz and microcline in a matrix of microscopic granules of milled quartz and microcline. Part of the matrix has been replaced and veined by quartz. The rock contains as much as 10 percent chlorite in fractures and interstitial to broken quartz and feldspar. Thorite, sericite, bastnaesite (?), hematite, and goethite occur along shears. The iron oxides may have formed by hydrothermal alteration of ferromagnesian minerals as is suggested by selvages of hematite and goethite within boundaries of minerals which have been replaced by quartz and chlorite.

About 100 feet east of the unnamed prospect pit No. 4 is the west end of an irregularly branching andesitic dike which extends across the canyon east of the prospect.

Radioactivity of the vein is as high as 1.3 mr per hour where the vein is thin, but is lower where the vein material is disseminated in gneiss. Radioactivity of the vein, 100 feet up the slope northwest of the prospect pit, is as much as 0.7 mr per hour, but a few feet northwest of this point it is negligible. Halfway to the top of the ridge northwest of the pit there is radioactivity as high as 0.6 mr per hour in line with the northwest-striking vein, and at the ridge crest about 400 feet northwest of the prospect pit the radioactivity is 0.06 mr per hour. Disseminated vein material 150 feet southeast of the prospect pit has radioactivity as much as 0.9 mr per hour; and radioactivity as much as several times background is detected locally along the vein for a distance of 200 feet southeast of the pit.

SIMON-RAY PROSPECT

A vein at the Simon-Ray prospect (fig. 9) was being explored for rare earths at the time the map (pl. 13) was being made in June 1952.

Tabular bodies of carbonate-barite-bastnaesite rock occur in a north-striking shear zone in pre-Cambrian metamorphic rocks just south of two parallel east-trending andesitic dikes and a cross-fault which cuts

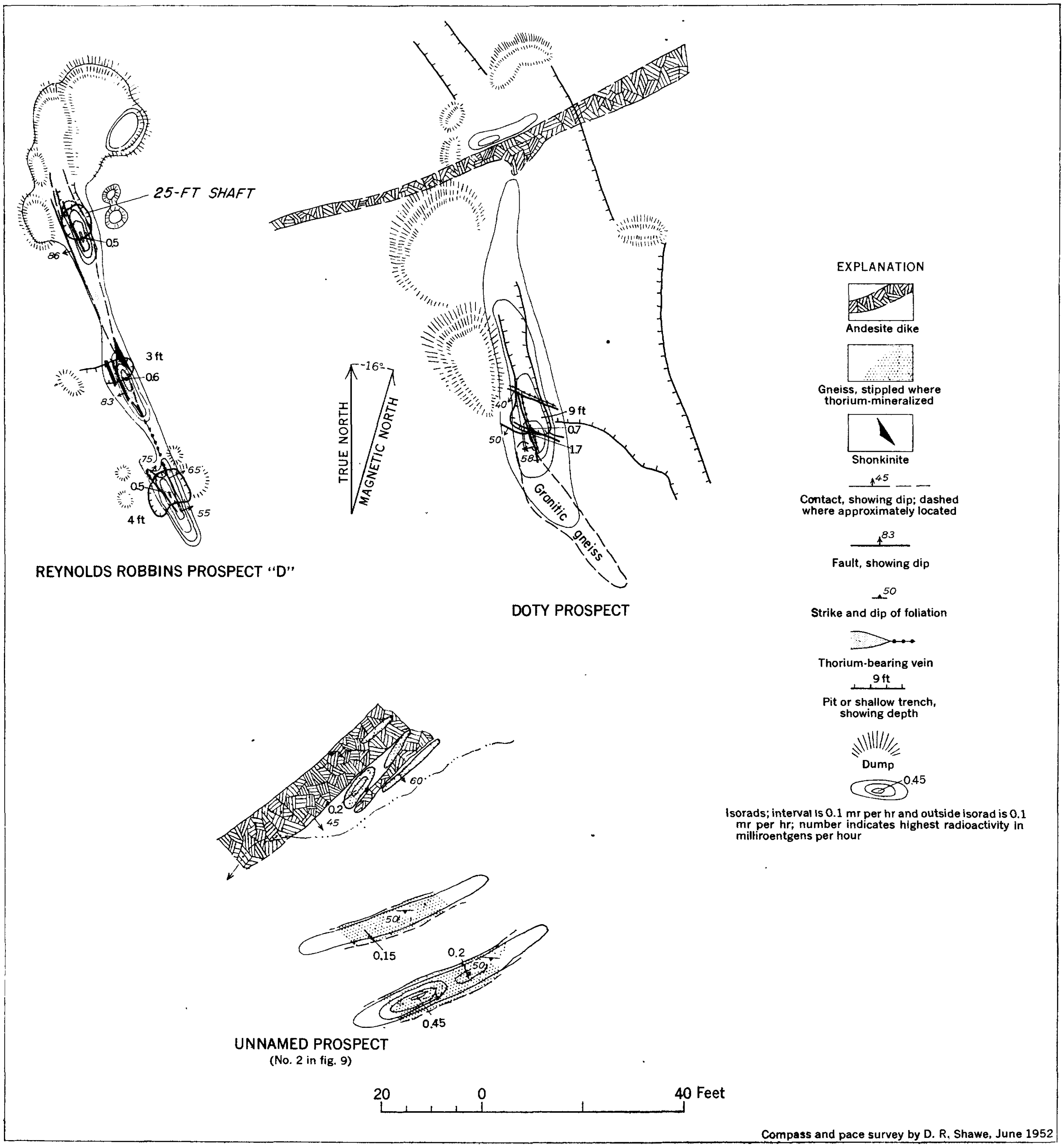

FIGURE 18.—Maps of three occurrences of thorium and rare earths in the Mountain Pass district.

the mineralized zone. Vein material constitutes no more than 25 percent of the shear zone near 225 S., 50 E. on the Simon-Ray map grid (pl. 13). The vein is disseminated in broken and altered gneiss containing crocidolite and phlogopite. Near 50 S., 25 W. and 350 S., 50 E. (pl. 13), coarse-grained shonkinite several inches thick occurs at the edge of the vein, and a few fragments of shonkinite are enclosed in the carbonate rock. A lens of shonkinite in the gneiss is parallel to and a few feet east of the vein at 350 S., 50 E. Radioactivity of the reddish vein material is about 0.1 to 0.15 mr per hour, and the radioactvity of a few yellow-brown streaks, 1 to 2 inches thick and as long as a foot, is as high as 0.35 mr per hour.

UNNAMED PROSPECT NO. 1

At the unnamed prospect No. 1 (fig. 9), a silicified carbonate vein, striking slightly north of west, is exposed for about 50 feet west of its intersection with a reddened shear zone which strikes northwest in pre-Cambrian metamorphic rocks. The vein has radioactivity about 0.06 mr per hour, which is slightly higher than the 0.04 mr per hour background. An area about 50 feet long and 3 to 10 feet wide along the shear zone, in hematitic thorite-bearing rock, has radioactivity ranging from 0.1 to 0.2 mr per hour.

UNNAMED PROSPECT NO. 2

In the canyon just south of the Goulder Goulch prospect and north of the Doty prospect (fig. 9) is a small area of abnormal radioactivity in gneiss adjacent to an andesitic dike (see fig. 18). As seen in thin section, the andesite has phenocrysts of hornblende, pleochroic from pale yellow to light greenish brown, and andesine, as long as 2 mm, which together make up 20 percent of the rock. Fine-grained hornblende, andesine, and magnetite, less than 0.25 mm in size, constitute most of the groundmass. Percents of the minerals in the thin section of the hornblende andesite are given on page 26.

The andesite is in hydrothermally altered gneiss. A thin section of the gneiss shows goethite, fine-grained calcite, and siderite in fractures and replacing the gneiss. The quartz of the gneiss exhibits strain shadows. Parts of the gneiss adjacent to the andesite and in two lenticular areas southeast of the andesite are sheared and reddened by hematite associated with carbonate and thorite, and these parts show radioactivity as high as 0.45 mr per hour.

BULLSNAKE PROSPECT

At the north end of the workings at the Bullsnake prospect (fig. 19), a shonkinitic dike 2 feet thick, striking northwest, is exposed in a trench. The radioactivty of this dike is about twice background. South of the dike, a carbonate vein in a branching shear zone is exposed in several small pits. The largest pit has been dug on a vein of silicified, hematitic carbonate rock 4 feet thick, dipping 70° W., which narrows to 1 or 2 inches in thickness about 30 feet both north and south of the pit. Thin lenses of similar carbonate rock occur to the south along both branches of the shear zone. Hematite and thorite make up about 10 percent of the vein, quartz 45 percent, calcite 35 percent, and bastnaesite 10 percent.

DOTY PROSPECT

The Doty prospect is between the Windy and Goulder Goulch prospects (fig. 9), probably in the same shear zone. This zone, although shown as continuous in figure 9, is probably faulted between the Doty and Goulder Goulch prospects; the northern segment or segments of the thorium-bearing shear zone are offset to the west.

A trench 9 feet deep in the hillside at the Doty prospect (fig. 18) exposes several mineralized shears which are radioactive, one as much as 1.7 mr per hour. Ab-

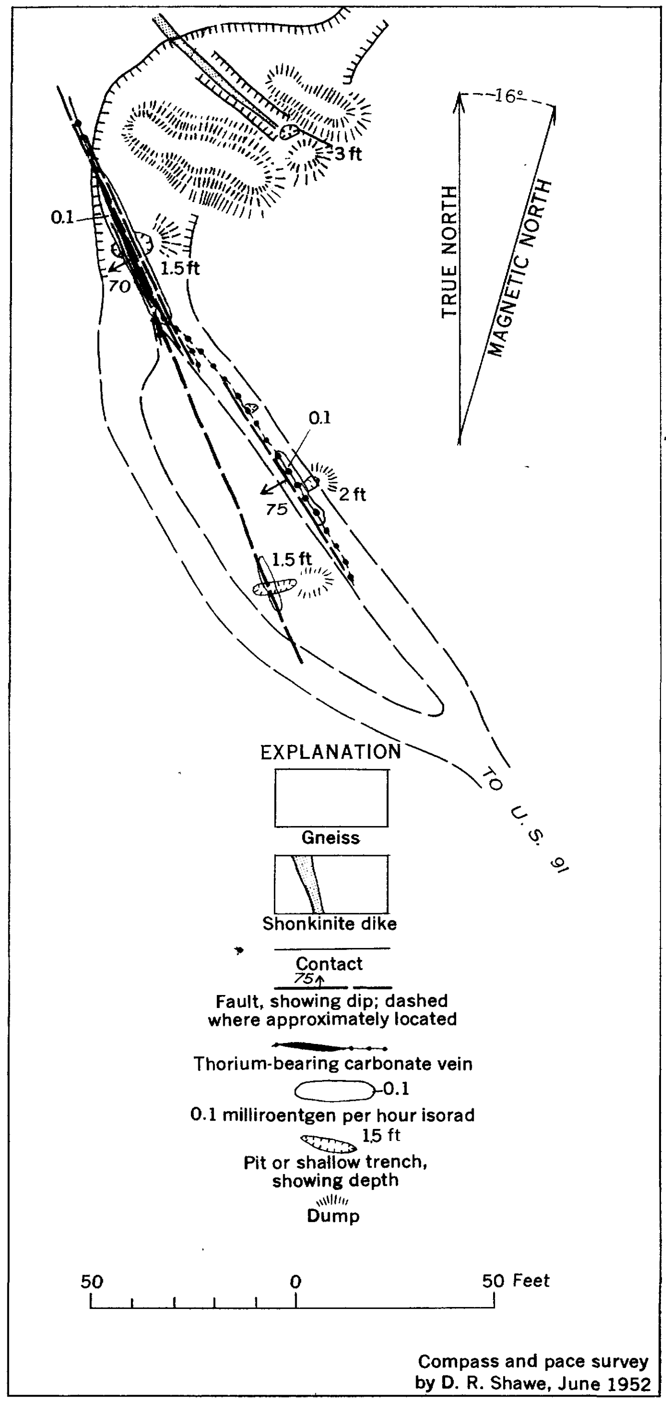

FIGURE 19.—Map of Bullsnake prospect.

normal radioactivity extends northward from a lenticular outcrop of reddened granitic gneiss along a north-striking mineralized shear to an andesitic dike which strikes about N. 60° E. The dike, which is not abnormally radioactive, branches where it intersects the radioactive zone. Abnormal radioactivity occurs at a point just north of the dike in line with the radioactive area to the south.

Abundant hematite and some thorite occur in lenses half an inch thick or less in the mineralized shears. A thin section of the radioactive granitic gneiss shows some mylonitization; hematite and probably thorite impregnate the rock along a fracture.

CANDY AND CAKE NO. 3 PROSPECT

The Candy and Cake No. 3 prospect is on a northwest-striking shear zone in the pre-Cambrian metamorphic rocks (fig. 9). The workings consist of a pit 6 feet deep in red-stained radioactive gneiss in the shear zone. Hematite and thorite occur in the sheared gneiss which contains abundant yellow-brown goethite. Radioactivity of the shear zone is as much as 0.25 mr per hour in the pit, 0.2 mr per hour 15 feet northwest, and 0.1 mr per hour 10 feet southeast of the pit. The counter readings average 0.07 mr per hour for 90 feet southeast of this to a point where a scraped area 25 feet long exposes a mineralized strip 3 feet wide, in line with the shear zone at the prospect pit. Radioactivity in the scraped area is as much as 0.27 mr per hour. About 350 feet S. 20° E. of the Candy and Cake No. 3 pit, a small area shows local radioactivity as much as 0.08 mr per hour.

Radioactivity as much as 0.1 mr per hour occurs locally in yellow-brown, iron-stained, sheared gneiss on the opposite side of the wash east of the Candy and Cake No. 3 prospect.

ALICE PROSPECT

A carbonate vein 8 feet long in altered gneiss along a shear zone at the Alice prospect (fig. 8) was explored by one prospect pit 8 feet deep. The vein strikes N. 45° E., dips 65° NW., and is apparently a faulted segment of a longer vein. The exposed vein tapers from a width of 2 feet at the southwest end to about 6 inches at the northeast end. Laminations in the vein are shown by concentrations of hematite and goethite parallel to the contacts. The hematite-rich and most radioactive part, in which radioactivity is as high as 0.9 mr per hour, probably represents less than 5 percent of the vein. A thin section of this radioactive material contains about 30 percent hematite and thorite, 40 percent barite, 10 percent quartz, and 20 percent goethite.

MODE OF ORIGIN OF THE RARE-EARTH DEPOSITS AND CARBONATE ROCKS

SUMMARY OF EVIDENCE

Any hypothesis that satisfactorily accounts for the origin of the carbonate rocks, the concentration of uncommon elements, and the association with potash-rich igneous rocks in the Mountain Pass district should take into consideration the following facts:

1. The pre-Cambrian foliated rocks have had a complex and diverse origin. They range in composition from ultrabasic to the predominantly granitic, and probably include igneous injection rocks and metamorphosed sedimentary and volcanic rocks. Limestone or dolomite of sedimentary origin is not known in the pre-Cambrian rocks of the district.

2. The potash-rich rocks and carbonate rocks are younger than the foliation of the gneisses but are also of pre-Cambrian age. Monazite in the Sulphide Queen carbonate body is dated as pre-Cambrian in age. The andesitic dike rocks are distinctly younger than the potash-rich rocks and probably are of Mesozoic or post-Mesozoic age.

3. The potash-rich igneous rocks and the rare-earth- and thorium-bearing carbonate rocks are generally discordant to pre-Cambrian metamorphic rock structure. They occur in and are apparently restricted to a belt 6 miles long and about a mile wide in the pre-Cambrian rocks.

4. The essentially unfoliated igneous rocks, with the exception of the andesitic dike rocks, are remarkably potash-rich and soda-poor, although sodic amphiboles and pyroxenes occur in the soda-poor rocks. The potash-rich rocks are also relatively rich in such elements as rare earths, barium, and strontium.

5. The potash-rich igneous rocks, ranging from shonkinite through syenite to granite, show a systematic variation in chemical composition.

6. The sequence of emplacement of the igneous and carbonate rocks of the district, wherever definitely ascertainable, is consistently shonkinite, syenite, granite, shonkinitic dike rocks, carbonate rocks, and andesitic dike rocks. Each successively younger type discordantly cuts all the older rocks.

7. The late shonkinitic dike rocks are similar in composition to the early shonkinite, and are the only potash-rich dike rocks that have well-developed flow foliation.

8. The potash-rich igneous rocks and the carbonate rocks are genetically related and are products of a single geologic episode. This is indicated by their field relationships and by the consistent association of such types

in other parts of the world. The largest body of carbonate rock and the greatest concentration of carbonate veins lie alongside the largest shonkinite-syenite stock in the district.

9. The andesitic dike rocks are younger than faults which cut all other rocks of the district and are distinctly different from the older rocks in composition.

10. Some contacts between the potash-rich rocks and the gneiss are sharp and some are gradational. Locally near sharp contacts the potash-rich rock is finer-grained than in the main central part of the mass. Some contacts are transitional through a zone of mixed rock consisting of angular fragments of gneiss and potash-rich igneous rock in the shonkinite, syenite, or granite. In some places the gneiss adjacent to the igneous rock or the carbonate rock is enriched in potash feldspar, phlogopite, or biotite relative to gneiss away from the carbonate rock.

11. Contacts between the shonkinitic dike rocks and older rocks are sharp, and these dikes commonly have relatively fine-grained borders resembling chilled margins.

12. Shearing occurred after the emplacement of much of the carbonate rock, and some rare-earth minerals occur along shear planes, especially in the Sulphide Queen carbonate body.

13. Along the shear zones that cut the potash-rich rocks but not the andesite dikes, the wall rocks are altered and rare-earth and thorium minerals have locally been deposited.

14. The carbonate rocks have an exceptionally high content of the rare earths, barium, strontium, and other uncommon elements.

15. The large Sulphide Queen carbonate body is mineralogically and structurally similar to some of the smaller veinlike carbonate bodies.

16. The Sulphide Queen carbonate mass is discordant to the pre-Cambrian foliation, the foliation in the carbonate rock is conformable to the walls of the body and commonly is at an angle to the foliation of the adjacent gneiss, and breccia fragments of assorted syenitic and gneissic rocks occur in the carbonate rock. Similar breccia fragments also occur in several of the thin tabular carbonate bodies.

17. Contacts of most of the carbonate rock with older rocks are sharp, but in many shear zones the carbonate permeates the wall rocks along many veinlets.

18. Typical contact metamorphic silicate minerals such as diopside, wollastonite, tremolite, idocrase (vesuvianite), and garnet have not been found in the carbonate rocks.

19. Phlogopite or biotite commonly occurs as a thin zone between carbonate material and adjacent or included feldspathic rocks such as syenite and gneiss.

20. Crocidolite and chlorite occur as late minerals chiefly along shear planes in the carbonate and potash-rich rocks and in the adjacent altered gneiss.

21. Many of the concentrations of thorium and rare earths are in mineralized shear zones, and in the area south of U. S. Highway 91 many of the richer deposits occur near the intersections of Tertiary (?) andesitic dikes with the shear zones.

Carbonate rocks, alkalic igneous rocks, and relatively large concentrations of certain uncommon elements are associated in many districts of the world, and various hypotheses have been set forth to explain the association. The most pertinent among them are the metamorphism of pre-Cambrian saline deposits (Jensen, 1908), limestone syntexis (Daly, 1918), magmatic differentiation (Bowen, 1928), magmatic differentiation processes with volatile substances such as CO_2 and F as important factors (Smyth, 1913), and the action of highly energized alkali-rich emanations, from an unknown deep-seated source, on sialic rocks (Holmes and Harwood, 1936, p. 249). In many areas the limestone syntexis hypothesis (Daly, 1918) has been used to explain the association of carbonate rock and alkalic igneous rocks, and has become well established as one explanation for the association. In other areas, such as Alnö Island, Sweden; Fen, Norway; and a number of South African localities, no sedimentary limestone is exposed within many miles of the complex of alkalic and carbonate rocks, and for these areas some geologists have attributed the carbonate, as well as alkalic rock constituents, to a magmatic source.

The close spatial association of the carbonate and potash-rich rocks at Mountain Pass, as well as similar associations elsewhere in the world, indicates that the origin of one rock type involves the other also. The leading hypotheses, as they apply to the Mountain Pass problem, are of three kinds according to whether the carbonate material in the veins and Sulphide Queen carbonate body originated from Paleozoic sedimentary carbonate rock, from pre-Cambrian sedimentary carbonate rock, or from magmatic sources presumably in pre-Cambrian time.

POSSIBLE PALEOZOIC SEDIMENTARY ORIGIN OF CARBONATE ROCK

Thick sections of limestone and dolomite of Paleozoic age occur just west of the Clark Mountain fault and formerly covered the entire district. These sedimentary carbonate rocks might be considered as a possible source of the carbonate in the veins and the Sulphide Queen carbonate body and, by limestone syntexis, to have played a part in the development of the potash-rich alkalic rocks.

The basal Cambrian rocks were deposited probably at least 3,000 feet above the present erosion surface in the Sulphide Queen area (see cross section, pl. 1). The Cretaceous (?) volcanic rocks that lie on Jurassic sandstone south of Grover Spring provide evidence that magma has reached the surface through sedimentary rocks of Paleozoic age in the district. The limestone and dolomite of Paleozoic age west of the Clark Mountain fault show no other evidence, such as contact metamorphic rocks, to suggest intrusion, stoping, and assimilation by magma. Furthermore, there are no large igneous rock masses exposed in the district that might have reacted with limestone, although a large body of quartz monzonite of post-Paleozoic age, which was not studied in the investigation, extends southward from a point about 3 miles south of Mountain Pass.

The Sulphide Queen carbonate body could not of itself be a faulted block of limestone of Paleozoic age, for the irregular contacts with the pre-Cambrian gneiss are not fault contacts, and no combination of faults can reasonably account for this mass of carbonate rock as a faulted block from the overlying rocks of Paleozoic age which were several thousand feet above the metamorphic complex in the vicinity of the Sulphide Queen mine.

For structural reasons, therefore, it seems unlikely that Paleozoic limestone and dolomite played any part in the petrogenesis, and this is further indicated by the pre-Cambrian age of the monazite in the Sulphide Queen carbonate body.

POSSIBLE PRE-CAMBRIAN SEDIMENTARY ORIGIN OF THE CARBONATE ROCK

As a working hypothesis it might be postulated that the carbonate rock originated from a pre-Cambrian sedimentary carbonate body, or carbonate-evaporite sequence, in the gneisses. No sedimentary carbonate rocks are known in the older pre-Cambrian complex of the Mountain Pass region, but this does not necessarily preclude the possibility that they may be present locally or below the surface.

If such a complex were intensely metamorphosed, volatile constituents such as carbon dioxide and lesser chlorine, fluorine, sulfur, and phosphorus might be abundant and migrate chiefly along fracture zones. Sufficiently high temperature along certain zones, in conjunction with an environment of abundant carbon dioxide, might cause such minerals as potash feldspar, sodic amphiboles and pyroxenes, phlogopite, and calcite—minerals typical of shonkinite—to form in the gneisses by replacement. Extreme temperatures locally might cause the more fusible constituents of the gneiss, such as quartz and feldspar, to melt and replace the surrounding gneiss, forming syenite or granite, some of which might be mobilized and intruded as dikes. According to this hypothesis, the late shonkinitic dikes might be explained by the eventual complete fusion (rheomorphism) of the shonkinitic material and its injection as a magma to form the dikes.

Under such extreme metamorphism, a carbonate lens would presumably be mobilized, reconstituted, and squeezed into discordance with the foliation. Possibly the dolomitic parts of the Sulphide Queen carbonate body represent less-metamorphosed carbonate rock that was intruded or replaced by, and included in, the more highly metamorphosed calcite-barite-bastnaesite rock. Subsequent, and possibly much later, hydrothermal solutions may have further redistributed some of the constituents of the carbonate rock and thus account for some of the veinlike bodies.

The abundance of rare-earth elements, strontium, and barium in the veins and the Sulphide Queen carbonate body is not satisfactorily explained by derivation from a pre-Cambrian sedimentary source. Known sedimentary rocks and present-day sediments do not contain these elements in such exceptional concentrations as are found in the Mountain Pass rocks. For the carbonate body to be of pre-Cambrian sedimentary origin would require these uncommon elements to have been present in concentrations unknown in any other sedimentary rocks, or to have been concentrated from other parts of the pre-Cambrian complex by a process of metamorphic differentiation, or to have been introduced into the carbonate rock from a magmatic source.

If the rare elements from a magmatic source were emplaced in preexisting sedimentary carbonate rock, the proximity of the Sulphide Queen carbonate body and the largest shonkinite-syenite body might be fortuitous, the carbonate rock merely being a favorable host for the rare elements derived from an igneous source. It seems unlikely that this is a chance association, however, for there are many examples of similar associations in the world.

The hypothesis that the carbonate rocks were derived from a pre-Cambrian sedimentary limestone or dolomite is not entirely adequate to explain the consistent order of emplacement of the several potash-rich igneous rocks followed by the carbonate rocks, the absence of known sedimentary limestone in the older pre-Cambrian complex of this region, and the concentrations of uncommon elements in the carbonate rocks.

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POSSIBLE MAGMATIC ORIGIN OF THE CARBONATE AND POTASH-RICH ROCKS

The carbonate rocks and veins may have formed from late fluids containing carbon dioxide, rare earths, barium, fluorine, and other elements, as end products of the differentiation of a potash-rich magma, fractions of which crystallized earlier as the shonkinites, syenites, granites, and shonkinitic dike rocks. This hypothesis harmonizes with the sequence of emplacement and spatial association of the potash-rich and carbonate rocks; the discordance of carbonate bodies to the potash-rich rocks and to the metamorphic rock foliation; the evidence of intrusion of the Sulphide Queen carbonate body, such as its foliation, inclusions, wall-rock alteration, and discordant contacts; and the exceptional concentration of rare earths, barium, and other uncommon elements. The relatively high content of barium and strontium in the potash-rich rocks, shown in tables 4 and 5, is further evidence of the close genetic relation of the baritic carbonate rocks to the potash-rich rocks.

Certain theoretical problems are difficult to explain by magmatic hypotheses, such as the origin of a magma of a composition that would yield the potash-rich igneous rocks and the remarkable concentrations of rare earths, carbon dioxide, barium, and other uncommon constituents of the carbonate rocks. The mechanism of transport and emplacement of the rare constituents, the carbonate, and the barite is not well known. If derived from a magmatic source, was the carbonate rock deposited from a relatively viscous carbonate magma or from dilute hydrothermal solutions? The Sulphide Queen carbonate body may have formed from a relatively viscous magmatic differentiate, with abundant volatile constituents such as carbon dioxide, fluorine, sulfur, and water, or it may have formed from less concentrated hydrothermal solutions.

At least some of the veinlike carbonate bodies were formed by deposition from hydrothermal solutions. Some veins in the Birthday area have an obscure banding which could be interpreted as formed by mineralization along reopened channels, but crustification has not been observed in any of the veins. Some of the veins in the Birthday area, such as the ankerite-barite type, appear to have developed by the progressive replacement of the shonkinite along a host of subparallel shear planes, and commonly the mafic minerals of the surrounding shonkinite are altered. Other veins, particularly those of calcite, barite, and bastnaesite, have sharp contacts with the adjacent shonkinite, and some of these appear to have been formed along fractures in the shonkinite.

Critical in the interpretation of the origin of the veinlike carbonate bodies is a knowledge of the temperature of formation, at present inadequately known. The typical occurrences of primary bastnaesite (table 9) in pegmatites and in thin contact zones and veins closely associated with intrusive igneous rock suggest formation of this mineral at relatively high temperatures, perhaps of the order of 400° C. Fersman, quoted by Turner and Verhoogen (1951, p. 332), cites fluocarbonates of Ca, Mg, Fe, and Mn as forming during the hydrothermal stage of pegmatite deposits (less than 400° C.). According to Lindgren (1933, p. 637) specularite, which occurs with bastnaesite in many places in the district, is commonly but not invariably associated with high-temperature veins. Most of the minerals, fluorite, quartz, and carbonates, are not indicative of specific temperatures. Many of the minerals, including bastnaesite, barite, fluorite, quartz, and calcite, formed at several stages, and probably a wide range of decreasing temperatures is represented between the crystallization of coarse crystals of bastnaesite and the deposition of fluorite along tiny fractures that cut the main masses of vein minerals.

On the basis of their chemical properties, the rare earths may be divided into three groups, commonly called the cerium, terbium, and yttrium groups. In general, rare earths of the cerium group show an affinity for alkalic rock types, while the yttrium group is more commonly found in granite pegmatites (Rankama and Sahama, 1950, p. 523). In the Mountain Pass district, the major intrusive bodies are shonkinite and syenites of alkalic affinities, and the rare earths are almost entirely of the cerium group, consisting largely of cerium, lanthanum, neodymium, and praseodymium. The rare earths, according to Rankama and Sahama, tend to occur in small amounts in the major rock-forming minerals and in the accessory minerals of igneous rocks. Because of their large ionic radii, the rare earths are also thought to be concentrated in the residual fluids of magmatic crystallization, as indicated by the prevalence of rare-earth minerals in pegmatites.

Part of the present laboratory investigations of the U. S. Geological Survey includes chemical analyses of the major rock types and minerals of the Sulphide Queen area. The few analyses of these rocks now available show abnormal concentrations of rare earths, barium, and other elements common in the veins, providing further evidence to link the carbonate mineralization with the introduction of the potash-rich igneous rocks of the Mountain Pass district.

SUMMARY OF COMPARABLE AREAS

The association of carbonate and alkalic igneous rocks, and its implications, have been discussed by many writers, for example Smyth, 1913; Daly, 1933, p. 505–

512, 564–565; Shand, 1947, p. 304, 312–329; Turner and Verhoogen, 1951, p. 341–342. The origin of the rocks and their associations remain a fundamental problem, and in most individual districts the interpretations are controversial. The Mountain Pass district typifies this association of alkalic rocks, carbonate rocks, and extraordinary concentrations of certain uncommon elements, in a metamorphic complex that is dominantly migmatite and granitic gneisses. In comparison with usage in other regions, most of the carbonate rock at Mountain Pass could be classed as "carbonatite," that is, intrusive carbonate rock regardless of origin.

Table 14 summarizes certain geologic features of several comparable areas. Particular emphasis is given to those features that most closely resemble the rocks and associations at Mountain Pass, such as the spatial relations between carbonate and alkalic igneous rocks, the compositional varieties and the banding or other structural features of the carbonate rocks, composition of the igneous rocks, contact relations, and minerals containing uncommon elements. The geologic age of the various complexes ranges widely. Some are probably pre-Cambrian, while others, such as the South African ones, have been dated as Permian or post-Permian to Tertiary in age.

Many similarities and some differences are apparent in a comparison of Mountain Pass with other carbonate rock-alkalic rock complexes.

Similarities include (see table 14):

1. The carbonate rock is commonly intrusive (Alnö Island, Chilwa series, Homa Bay area).
2. A distinction is made in many districts among several varieties of carbonate rock, commonly calcitic and dolomitic (Fen, Alnö, Spitzkop).
3. Mineral assemblages are similar, and minerals such as apatite, dark micas, fluorite, soda-amphiboles, and hematite are commonly found in the alkalic and the carbonate rocks.
4. Structural features of the carbonate rock, such as lack of bedding, presence of banding or foliation which generally conforms to walls and dips steeply (Tororo, Homa Bay area, Iron Hill).
5. Inclusions of altered wall rock in the carbonate rock, deflecting flow structures (Chilwa series, Tororo, Alnö).
6. The common occurrence of small veinlike carbonate bodies, as well as large masses.
7. Extraordinary concentrations of rare elements in carbonate rock or in alkalic rock complexes (Tororo, Fen, Iron Hill).
8. Fenitic alteration locally along contacts, as in many regions.
9. Widspread soda-amphibole in carbonate rocks and their wall-rocks (Chilwa series, Iron Hill). (*See also* Larsen and Pardee, 1929.)

Among the differences are:

1. The lack of feldspathoids in the Mountain Pass igneous rocks, except for the pseudoleucite (?) noted in one thin section of shonkinite from the Birthday area.
2. The absence of related volcanic rocks which are present in some East African localities (Chilwa series, Homa Bay area). (*See also* Wagner, 1922.)
3. The absence of concentric or ring structure (Alnö, Tororo, Spitzkop).
4. Lime-silicate minerals are absent at Mountain Pass but present at Magnet Cove, Homa Bay area, Uganda occurrences, and some others.
5. The concentration of bastnaesite and barite at Mountain Pass.
6. The scarcity at Mountain Pass of titanium-niobium minerals which occur at Magnet Cove, Fen, Kaiserstuhl, Tororo.
7. Relatively little magnetite is associated with Mountain Pass carbonate rock in comparison with those at Fen, Jacupiranga, Dorowa.

ECONOMIC OUTLOOK

The rare-earth mineral deposits at Mountain Pass offer great promise as a source of the rare-earth metals and barite. The amount of these materials produced depends upon several factors. One of these is the demand for rare earths by industry, a demand which has been relatively small but may increase as new uses for the rare earths are found. Another factor is the development of the most satisfactory milling methods for the separation of the rare-earth minerals, barite, and other constituents of the Mountain Pass ores. Byproduct barite should find a ready market, because the district is relatively close to southern California oilfield operations.

The Sulphide Queen carbonate body, because of its large size, is the most easily mined and most promising source of rare-earth metals in the district. Although some of the thin veins are locally richer than the average Sulphide Queen carbonate rock, they are less easily mined and, judged by the Birthday veins, likely to be irregular or discontinuous in depth. Should the value of thorium increase, some of the thinner veins and radioactive shear zones might constitute sources of both thorium and rare earths, for, in general, richer concentrations of thorium are found in the shear zone deposits than in the Sulphide Queen carbonate body. The thorium which makes up a small fraction of a percent of the Sulphide Queen body might constitute a potential byproduct if the demand for thorium is sufficient to warrant recovering it and methods of recovery are satisfactory.

The Sulphide Queen carbonate body is irregular in shape at the surface, and is probably so at depth, but there is no geologic reason to expect marked changes in thickness or overall rare-earth content at a shallow depth. The thinner veins and parts of mineralized shear zones are not uncommonly discontinuous or arranged in echelon. Individual bodies in the mineralized shear zones have not been explored in depth and are likely to be less persistent than the large Sulphide Queen mass.

Tables 10–13, in the appendix to this report, give analytical data for about 140 samples, chiefly the rare-earth and thorium contents. These results are summarized by rock type in table 10, which brings out clearly the high rare-earth and thorium content of the carbonate rocks in comparison with the igneous rocks. Table 10 also demonstrates the predominance of thorium over uranium in accounting for the radioactivity, which is expressed here as equivalent uranium. The tables illustrate the considerable variation in rare-earth and thorium content in individual deposits.

The field and laboratory information assembled by the U. S. Geological Survey on the various deposits in the Mountain Pass district permits the estimate of an inferred reserve for the district in excess of 25 million tons of rock containing 5 to 10 percent rare-earth oxides, 20 to 25 percent barite, and a small fraction of 1 percent of thoria. Cerium is the preponderant rare-earth element, lanthanum and neodymium next in abundance, and praseodymium and samarium less abundant. The geologically potential reserve in the whole district is of vaster magnitude and may exceed 100 million tons, containing about 5 percent of rare-earth oxides, or more than 10 billion pounds of rare-earth oxides. This represents the greatest concentration of rare earths known in any type of rock or district in the world.

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APPENDIX

ANALYTICAL DATA

TABLE 10.—*Summary of analytical data, in percent*

[The number of samples analyzed is in parentheses]

Rock unit	*Equivalent uranium*	*Uranium (chemical)*	*ThO_2*	*Combined rare-earth oxides*
Shonkinite and biotite-rich syenite	0.006–0.012 (10)	0.002–0.005 (10)	<0.1 (5)	0.02–0.08 (5)
Shonkinite dike	0.008 (1)	0.004 (1)	----	----
Granite	0.005–0.013 (5)	0.002–0.013 (5)	<0.1 (1)	0.07 (1)
Carbonate veins	0.004–0.55 (49)	0.001–0.020 (34)	<0.1–2.39 (37)	0.00–18.64 (53)
Sulphide Queen carbonate body	0.001–0.016 (29)	0.002–0.007 (3)	<0.1 (19)	0.00–38.92 (59)

TABLE 11.—*Analytical data for igneous and metamorphic rock samples, in percent*

Sample number	Equivalent uranium	Uranium (chemical)	ThO_2	Combined rare-earth oxides	Remarks
1A[1]	0.009	0.002	<0.1	0.02	Shonkinite, east wall of Birthday discovery vein.[2]
2A	.007	.003	----	----	Shonkinite, Birthday area.[2]
3A	.007	.002	----	----	Shonkinite, composite body northeast of Grover Spring.
4A	.012	.005	<.1	.05	Do.
5A	.012	.003	<.1	.08	Do.[3]
6A	.007	.002	----	----	Do.[4]
7A	.012	.003	<.1	.04	Do.[5]
8A	.006	.002	----	----	Shonkinite, Birthday area.[2]
9A	.007	.002	----	----	Do.[2]
10A	.008	.002	<.1	.03	Do.[4]
11A	.008	.004	----	----	Late shonkinitic dike, Birthday area.[2]
12A	.013	.013	<.1	.07	Granite, Mineral Hill.
13A	.005	.003	----	----	Fine-grained granite dike, Birthday area.[2]
14A	.008	.004	----	----	Do.[2]
15A	.010	.003	----	----	Do.[2]
16A	.006	.003	----	----	Do.[2]
17A[6]	.013	.002	<.1	.01	Metadiorite, Birthday No. 10 claim, west of Birthday area.

[1] Mn is 0.07 percent. [2] Location shown on plate 8. [3] Pegmatitic part. [4] Mafic syenite. [5] Shonkinite dike. [6] Mn is 0.06 percent.

See notes to tables 10–13, p. 69.

TABLE 12.—*Analytical data of samples of carbonate rock from the area of the Sulphide Queen carbonate body, in percent*

Locality (pl. 8)	Equivalent uranium	Uranium (chemical)	ThO_2	Combined rare-earth oxides	P_2O_5
1B [1]	0.009	0.007	<0.1	2.70	
2B [2]	.014	.007	<.1	1.10	
3B	.004		<.1	2.42	
4B	.005		<.1	.83	
5B	.006		<.1	2.94	
6B	.013	.002	<.1	4.12	
7B				1.00	
8B	.007		<.1	3.87	
9B	.003			1.04	
10B	.003			.75	
11B	.004			.52	
12B	.004			.76	
13B	.011			1.27	
14B	.001			1.91	
15B	.007			4.83	
16B	.005			6.82	
17B	.003			4.45	
18B	.009		<.1	None	
19B	.004		<.1	1.10	
20B	.007			7.77	
21B				24.20	
22B				38.92	
23B				5.21	
24B				11.80	
25B	.005		<.1	9.34	0.30
26B	.004		<.1	11.94	.45
27B	.008		<.1	13.10	.25
28B	.005		<.1	8.90	.46
29B	.001		<.1	12.65	.45

[1] Mn is 0.13 percent.
[2] Mn is 0.31 percent.

TABLE 12.—*Analytical data of samples, etc.*—Continued

Locality (pl. 8)	Equivalent uranium	Uranium (chemical)	ThO_2	Combined rare-earth oxides	P_2O_5
30B	0.008		<0.1	12.87	0.19
31B	.005		<.1	9.34	.43
32B	.003		<.1	7.91	.30
33B	.004		<.1	8.93	.85
34B	.016		<.1	9.64	.14
35B				10.26	
36B				7.08	
37B				.36	
38B				.78	
39B				4.22	
40B				1.86	
41B				3.13	
42B				2.78	
43B				1.86	
44B				2.46	
45B				.86	
46B				2.24	
47B				3.10	
48B				1.82	
49B				1.26	
50B				10.02	
51B				8.90	
52B				10.44	
53B				7.92	
54B				3.34	
55B				13.94	
56B				26.10	
57B				26.88	
58B				10.96	
59B				9.22	

TABLE 13.—*Analytical data for veins and carbonate rocks, in percent*

Sample number	Equivalent uranium	Uranium (chemical)	ThO_2	Combined rare-earth oxides	Mn	Remarks
1C	0.086		0.58			Sulphide King claim; 10-ft channel across vein.[1]
2C	.026		.13			Sulphide King claim; 4-ft channel across vein.[1]
3C	.016		<.1			Do.[1]
4C	.031		.23	8.82		Robbins prospect, 2,000 ft south of Mexican Well; 2½-ft vein.
5C	.13	0.002	.70	4.58		Pit 500 ft northwest of 4C; 9-ft chip sample across shear zone.
6C	.061	.002	.33	8.94		Pit 200 ft N. 28° W. of 5C; chip sample across shear zone.
7C	.005	.006				Vein; west wall of pit.[1]
8C	.005	.004				Do.[1]
9C	.021	.003				Carbonate-barite-goethite vein in pit.[1]
10C	.011	.004				Do.[1]
11C	.076	.003	.30	2.03		Carbonate-bastnaesite-barite vein in pit.[1]
12C	.080	.004	.41	3.48		Do.[1]
13C	.080	.002	.37	14.35		Limonite-rich vein in pit.[1]
14C	.092	.006	.39	6.70		16-ft drift from Birthday pit; chip sample of vein.[1]
15C	.097	.001	.39	7.66		Do.[1]
16C	.047	.008				Vein in pit; grab sample.[1]
17C	.032	.005				Composite sample; veins and wall rock.[1]
18C	.29	.001	1.31	1.14		Goethite-rich carbonate vein.[1]
19C	.004	.001				Quartz vein with minor barite.[1]
20C	.029	.005				Alice prospect, pit 2,175 ft south of Birthday shaft.
21C	.008		<.1	.45		Chip sample, veins near road fork 1,300 ft south-southeast of Sulphide Queen shaft.[1]
22C	.005		<.1	.94		North of 21C.[1]
23C	.006		<.1	4.81		Vein in gully, 500 ft south-southeast of Sulphide Queen shaft.[1]
24C	.004		<.1	1.46		Same vein as 23C, near Sulphide Queen mill.[1]
25C	.008		<.1	.58		Chip sample; vein near Sulphide Queen mill.[1]

See footnote at end of table.

TABLE 13.—*Analytical data for veins and carbonate rocks, in percent*—Continued

Sample number	Equivalent uranium	Uranium (chemical)	ThO_2	Combined rare-earth oxides	Mn	Remarks
26C	0.006		<0.1	2.08		Chip sample; vein 650 ft north of Sulphide Queen shaft.
27C	.11	0.009	.37	5.18		Chip sample of 40-in vein at Windy No. 1 pit.
28C	.019		<.1	.29		4-ft width of sheared gneiss, Windy prospects.
29C	.13		.34	2.61		Chip sample; fluorite-bearing carbonate vein, Windy prospects.
30C	.018		<0.1	0.05		Three-foot width of sheared gneiss in pit 2,100 ft N. 43° W. of Windy No. 1 pit.
31C	.23	.007	1.19	8.42	0.26	Birthday discovery pit, face of drift.[1]
32C	.39	.003	2.07	8.92	.26	Birthday discovery pit; carbonate vein, west wall of drift.[1]
33C	.058	.007	.25	7.20	.29	Birthday discovery pit; drift.[1]
34C	.19	.005	1.03	10.78	.26	Do.[1]
35C	.20	.007	.96	9.39	.21	Do.[1]
36C	.023	.008		17.80	.30	Birthday discovery pit; face of drift.[1]
37C	.14	.007	.54	17.00	.40	Do.[1]
38C	.55	.005	2.39	6.25	.50	Birthday discovery pit; near surface.[1]
39C	.085	.010	.25	14.14	.20	Do.[1]
40C	.37	.020	2.00	10.03	.38	Do.[1]
41C	.014	.006		.98	.02	Altered rock in shear zone; 3d level, Sulphide Queen mine.
42C	.045	.013	.23	4.65	.54	Carbonate-barite vein, 4th level; Sulphide Queen mine.
43C	.021	.007		.38	.05	Altered rock in shear zone; 3d level, Sulphide Queen mine.
44C	.025	.006	<.1	.71	.02	Sulfide-rich lens 2 in thick; 2nd level Sulphide Queen mine.
45C	.014	.001		.08	.08	Quartz vein, Birthday No. 10 claim, west of Birthday shaft.
46C	.008	.006	<.1	8.57	.03	Siliceous vein.[1]
47C	.13		.62	16.93	.11	Carbonate vein with thorite(?).[1]
48C	.12		.59	18.64	.21	Same vein as 47C, limonitic.[1]
49C				1.95		Grab sample, carbonate vein.[1]
50C				1.56		Do.[1]
51C				1.38		Do.[1]
52C				4.70		Do.[1]
53C				2.14		Do.[1]
54C				.82		Do.[1]
55C				3.36		Do.[1]
56C				2.10		Do.[1]
57C				.24		Do.[1]
58C				3.98		Do.[1]
59C				.64		Do.[1]
60C				1.06		Do.[1]
61C				4.00		Do.[1]
62C				.00		Do.[1]
63C				8.94		Do.[1]
64C	.018	.002	<.1	.23		Do.[1]

[1] Location shown on plate 8.

NOTES TO TABLES 10 TO 13

Analyses of samples 1A–17A, 1B–6B, 8B–20B, 25B–34B, and 1C–48C by L. F. Rader, J. Rosholt, E. C. Mallory, W. Mountjoy, R. Dufour, R. G. Havens, H. Bivens, and G. W. Boyes, Trace Elements Section Denver Laboratory.

Analyses of samples 7B, 35B–59B, 49C–64C by M. K. Carron.

Analyses of samples 21B–24B by Smith-Emery Company, Los Angeles, Calif.

TABLE 14.—*Summary of 13 areas having rock associations comparable to those of Mountain Pass.*

Locality	*Principal references*	*Country rocks*	*Area of igneous rocks*	*Igneous rock types*	*Features of igneous rocks*	*Contact relations*	*Carbonate rock, size*	*Carbonate rock, mineralogy*	*Carbonate rock, structural features*	*Author's interpretation*
Mountain Pass, Calif.	This report	Pre-Cambrian granitic and mixed gneisses.	7 small intrusive bodies, the largest 6,300 ft long and 1,750 ft wide. Several hundred thin dikes.	Shonkinite, syenite, potash-rich granite.	Not foliated like pre-Cambrian gneisses. Fibrous soda-amphibole common along fractures. Wall rocks altered near carbonate veins.	Contacts both sharp and gradational. Fenitic alteration locally near igneous and carbonate rocks (see p. 18).	Sulphide Queen carbonate body is 937,000 sq ft. Thin veins abundant.	Calcite, dolomite, ankerite, siderite, barite, barian celestite, bastnaesite, parisite, monazite, quartz, crocidolite, phlogopite, biotite, allanite, magnetite, hematite, galena, pyrite, apatite, fluorite, and others (see p. 33).	Discordant carbonate body. Foliation due to elongation and alinement of barite grains, and shear planes containing crocidolite, barite, etc. Near margins the foliation generally conforms to contacts.	See p. 60–62.
Iron Hill, Colo.	Larsen, 1942	Pre-Cambrian gneisses and granites.	Complex occupies 12 sq mi.	Pyroxenite is 70 percent of complex. Uncompahgrite, ijolite, soda syenite, nepheline gabbro, quartz gabbro.	Great local variation in grain size and composition. Parts of pyroxenite are rich in vermiculite.	Where the pre-Cambrian granite has been impregnated with and replaced by aegirite and sodic amphibole, a rock identical with the "fenitized granite" of Brögger has been produced.	2 by 1¼ miles. Many carbonate veins cut the igneous and metamorphic rocks, and the large mass of marble.	Mostly dolomitic, partly calcitic. A few percent of apatite, limonite, pyrite, aegirine, soda-amphibole, phlogopite, microcline, albite, quartz, anatase, fluorite. Rare earths present in apatite.	Not bedded, but has steeply dipping foliation and lineation in many places, caused chiefly by apatite along shear planes and by orientation of minerals.	Main carbonate mass probably formed as hydrothermal deposit in throat of volcano, and is oldest rock of the complex. It may have been intruded as a carbonate magma or it may be an inclusion of pre-Cambrian marble.
Magnet Cove, Ark.	Williams, 1890; Washington, 1900; Landes, 1931; Ross, 1941, p. 23–26; Fryklund and Holbrook, 1950.	Sandstone of Paleozoic Age, novaculite, chert, and shale metamorphosed to slate.	2¼ by 2¾ miles.	Wide variety of Cretaceous igneous rocks characterized by nepheline and, in one of the abundant types, by pseudoleucite.	Several incomplete rings of igneous and metamorphic rocks, cut by dikes.	Paleozic rocks are altered near the complex. Hornfels is found within the igneous mass.	Many veins, tufa, and a coarse-grained calcite rock.	Veins contain calcite, dolomite, ankerite, microcline, albite, etc. Calcite rock contains monticellite, magnetite, apatite, dysanalite (perovskite), wollastonite, pyrite, vesuvianite, rutile, brookite, anatase, phlogopite, and thomsonite.	Tabular bodies and irregular masses.	Origin of calcite rock uncertain. Landes considered calcite rock a xenolith of sedimentary limestone. Other possibilities such as veins and magmatic carbonatite.
Alno Island, Sweden.	Von Eckermann, 1948.	Pre-Cambrian migmatite. No evidence of limestone of pre-Cambrian age within hundreds of miles.	3 miles in diameter.	Light, and dark-colored syenitic and nepheline syenitic rock types chiefly.	Complex has crude concentric structure. Von Eckermann believed igneous rocks originated partly as mobilized fenite and partly as igneous intrusive bodies such as radial dikes.	Migmatite grades inward, through a zone of fractured and iron-stained migmatite, to fenite. Fenite is of generally quartz syenitic, syenitic, or nepheline syenitic composition, formed by replacement of migmatite by aegirine-augite and potash feldspar chiefly.	Several small masses less than 0.3 mile wide. Many thin bodies, some with form of cone-sheets, radial dikes, ring dikes. Barite veins also present.	Calcite and dolomite rocks (sövite, rauhaugite, alvikite, beforsite), with biotite, apatite, pyroxene, quartz, pyrite, albite, orthoclase, fluorite, magnetite, ilmenite, melilite, olivine, sphene, perovskite, garnet, natrolite, chlorite, antigorite, barite, knopite (cerium-perovskite), pyrochlore, zircon.	Carbonate rock contains many altered inclusions of fenite wall rocks enriched in pyroxene. The fluidal banding of the carbonate rock bends around inclusions. The carbonate dikes have generally well-defined contacts and well-developed flow structure.	Magmatic liquid, consisting of mainly carbonates and other components, of low temperature (400°–600° C.). Intrusion reached surface through the explosive opening of a diatreme.
Fen, Norway	Brögger, 1920; Bowen, 1924 and 1926; Brauns, 1936; Tomkeieff, 1938.	Extensive pre-Cambrian granite. No sedimentary limestone.	4 sq km	Variety of igneous rocks, many containing nepheline, such as urtite, ijolite, melteigite. Dark rocks predominate. Contain variable amounts of calcite.	Locally the fenite appears to have been mobilized, forming independent dikes.	Enrichment of granite wall rock in albite and aegirine produced an alkali feldspar-aegirine rock—fenite—or the darker variety, tveitasite.	Carbonate rock forms at least half the area of the complex, chiefly in large masses but also in smaller veinlike bodies and in mixed carbonate-silicate rocks.	(1) Sövite, composed of essentially calcite, with apatite, biotite, manganophyllite, and microlite; (2) rauhaugite, composed of magnesium and iron carbonates, with apatite, barite (to 8 percent), and magnetite; (3) mixed carbonate-silicate rocks. Typical contact metamorphic minerals absent.	Within carbonate mass are patches of iron ore and hematite-magnetite-carbonate rocks ("Rodberg"). Gradations from carbonate rock, through mixed carbonate-silicate rocks, to the silicate wall rocks.	Brögger concluded that magmatic carbonate was derived from the melting of an older limestone below the pre-Cambrian granite. Bowen attributed carbonate rock to replacement. Brauns favored igneous origin.

Spitzkop, Sekukuniland, eastern Transvaal.	Shand, 1921; Strauss and Truter, 1950a, 1950b.	Pre-Cambrian red Bushveld granite and granophyre.	3 miles in diameter.	Alkalic rocks such as foyaite, ijolite, urtite, umptekite, quartz syenite, and alkali granite.	Ring dikes. Concentric sheeted structure with centripetal dip.	Fenite (Strauss and Truter). Grades inward from granite to alkali granite, quartz syenite, and red and white umptekite.	Circular area 4,000 ft in diameter in the complex near 1 edge. Also thinner dikes.	(1) gray calcite rock, with clots of apatite and magnetite; (2) dolomitic rock with apatite, magnetite, pyrite, limonite; (3) limestone containing pyrite, limonite, serpentinous material, fibrous amphibole; (4) impure limestone.	Type (1) has nearly vertical banding, concentric structure, and forms a narrow, complete outer zone; (2) is thinly laminated and forms main central part of mass, banding concentric and dips outward; (3) occurs in irregular veins cutting (1) and (2), (4) forms dikes as wide as 2 ft cutting the other varieties.	Shand interpreted carbonate rock as xenolith of Transvaal dolomite brought up 14,000 ft. Strauss and Truter considered it a product of magmatic differentiation.
Palabora, eastern Transvaal.	Shand, 1932; DuToit, 1932.	Pre-Cambrian granite and schist.	2 by 4 miles	Shonkinite, pyroxenite, syenite, and granite.	The younger granite cuts shonkinite and syenite. Sodic amphiboles and pyroxenes common in potash-rich rocks.	---	2 masses of limestone, the larger about ½ sq mile in area.	Carbonate rock locally contains pyroxene, orthoclase, magnetite, apatite, olivine, mica.	Limestone is cut by thin bodies of shonkinite and syenite, but not by granite.	Shand and DuToit interpreted as an inclusion of older limestone rather than a magmatic product.
Chilwa series, Southern Nyasaland.	Dixey, Smith, and Bisset, 1937.	Pre-Cambrian granitic gneisses and younger sediments. Limestone scarce in basement rock.	Nine vertical pipelike intrusions, 1 to 4 miles in diameter; 7 smaller vents, less than 0.25 mile in diameter.	Syenitic rocks include trachyte, solvsbergite, and syenites. Nepheline-bearing rocks, generally later than carbonate bodies, include foyaites, tinguaite, ijolite, nepheline syenite, nephelinite, and phonolite.	Alkalic rocks occur in and near vents filled with brecciated potash-rich feldspar rock. Sodic pyroxenes and sodic amphiboles occur in syenites, fenite, or granite.	Wall rocks commonly jointed, shattered, reddened by films of iron oxide. Feldspathic material introduced into joints and foliation planes. Pyroxene locally replaces some minerals. The most advanced alteration yields a feldspar-pyroxene rock comparable to fenite.	Carbonate bodies ranging from 0.25 to 3 miles in diameter occur in 5 of the larger complexes. Carbonate also occurs as matrix of agglomerate, and in discontinuous rings around nepheline syenite cores.	Calcite is chief carbonate, but iron and manganese carbonates are also present. Also apatite, magnetite, fluorite, biotite, strontianite, and veins of late quartz and chalcedonic silica.	Carbonate minerals in places are segregated into irregular masses or parallel streaks. Near-vertical banding is due to parallel arrangement of carbonate or feldspathic streaks. Angular fragments of feldspar rock are closely set in some limestone which has a flow structure marked by streaks of feldspar rock.	Vents formed at least in part by explosive action. Origin of limestone is closely connected with magma responsible for the vents and the orthoclase rocks. Present exposures were at least 7,000 ft below the original surface.
Shawa and Dorowa, Southern Rhodesia.	Mennell, 1946	Gneissic granite.	4 miles in diameter (Shawa); 1 by 2 miles (Dorowa).	Alkalic rocks consisting of ijolite, syenite, shonkinite, nordmarkite, granite, jacupirangite, pyroxenite, and serpentine.	Carbonate core is surrounded by rings of syenite, granite, serpentine, pyroxenite, and shonkinite.	Ring structures. Granite at border of complex differs from gneissic granite country rocks.	2 miles in diameter, nearly circular in plan (Shawa); 500 yd in diameter (Dorowa).	Most carbonate rock is dolomitic, and is locally ferruginous. Magnetite, asbestiform iron-bearing amphibole, apatite, mica. Apatite and magnetite in various proportions in apatite-magnetite rocks.	Carbonate rock has distinct foliation, cleavage, or banding. Masses of magnetite-rich rock at Dorowa are as much as 40 ft wide and 900 ft long.	Carbonate rocks related to the presumably volcanic and deeper-seated occurrences in other parts of Africa nearby.
Homa Bay area, Kenya.	Pulfrey, 1944	Greenstone and conglomerate.	Main ijolite mass is about 1 by 2 miles in plan.	Alkalic dike rocks such as ijolite, urtite, melteigite, nephelinite, phonolite, and shonkinite.	Abundant metasomatic replacement due to deuteric and hydrothermal fluids. Igneous masses are notably heterogeneous.	Fenite found locally. Xenoliths of ijolite are found in carbonatites and in the lavas.	Several bodies of carbonatite as much as a mile long.	Carbonate, some with melanite, phlogopite, vesuvianite, aegirine, aegirine-augite, apatite, and magnetite. Later ferriferous carbonatites cut the earlier carbonate rocks.	Carbonatites have crude ringlike or pluglike form. The silicates commonly show a marked streaming in planes that are generally vertical but are locally inclined or contorted.	Carbonatites of deep-seated rather than sedimentary origin.
Eastern Province, Uganda.	Davies, 1947	Granitic	4 volcanic centers, with carbonate cores; range from about 2 to 5 miles in diameter.	(1) granites with sodic hornblende; (2) kalisyenite, pulaskite, fenite, and their darker counterparts; (3) ijolite, nepheline syenite, melteigite, urtite, pyroxenites, dunite; (4) magnetite-apatite-phlogopite rock; (5) carbonatite.	Each complex is made up broadly of five roughly concentric belts, composed of the rocks indicated in preceding column. These are arranged successively from no. 1 nearest the walls, to no. 5 in the center.	Fenite aureoles. Syenitic rocks have formed in place from granite.	Largest carbonatite is 2½ miles in diameter. Others are about ½ by 1½ miles in plan. Small dikes of carbonatite also present.	Fairly pure limestone with widespread magnetite, apatite, phlogopite, pyroxene, hematite, and fluorite. Low magnesium content in carbonate; local siderite. At outer edge are minerals such as garnet, wollastonite, tremolite, koppite, and anatase.	Near contacts the rock types are commonly mixed, such as fenite mixed with limestone.	Carbonatite injected at lower temperature than the associated magnetite-apatite-phlogopite rocks and silicate igneous rocks.

TABLE 14.—*Summary of 13 areas having rock associations comparable to those of Mountain Pass*—Continued

Locality	*Principal references*	*Country rocks*	*Area of igneous rocks*	*Igneous rock types*	*Features of igneous rocks*	*Contact relations*	*Carbonate rock, size*	*Carbonate rock, mineralogy*	*Carbonate rock, structural features*	*Author's interpretation*
Tororo Hills, eastern Uganda	Williams, 1952; Davies, 1947.	Granite. No limestone recorded.	About 2 miles long.	Chiefly syenitic rocks.	Mostly syenitic rocks, with zone of mixed rocks locally near carbonate body.	Fenite aureole	Pear-shaped in plan, about 1½ miles long. Main mass is cut by innumerable thin calcitic dikes.	See above (Davies, 1947). Chiefly calcitic (alvikitic sovite). Some dolomitic segregations.	Lamellar flow structure, mostly parallel to the ring structures but showing turbulent flow around inclusions of fenite. Series of rings of varying grain size gives a "collar-structure" to the mass in plan. Dip of ring structure increases toward margins of the mass, making it funnel-shaped in cross section. Breccias along faults.	Carbonatite represents final phase in history of volcano. Ring features originated through the congealing in the conduit of the central part of the carbonate mass.
Jacupiranga, Sao Paulo, Brazil.	Derby, 1891	Pre-Devonian schist and granite, with some limestone or marble.	Abundant in area of 30–40 sq km.	Augite syenite, jacupirangite, foyaite, nephelinite, others.	------	------	A long narrow ridge of limestone occurs near the center of the jacupirangite area, but the contact with surrounding rocks could not be observed.	Coarse white marble, heavily charged in places with magnetite and apatite. Large flakes of hydrated biotite with crystal outlines appear to form a primary constituent of the rock, and allanite occurs in limestone near its border. Barite occurs in a magnetite-apatite-acmite-barite-chalcedony rock.	------	Derby presumed the limestone to be an inclusion of Cambrian age.
Azov Sea region, Russia.	Kuzmenko, 1940.	------	------	Alkaline hornblende granite, with aegirine and amphibole of crossite-crocidolite type, syenites, and transitional rocks between syenite and granite.	------	------	Petrovsko-Gnutovo fluorite-carbonate vein is 0.3–2.85 m. thick.	Carbonates, fluorite, quartz, chalcedony, sphalerite, galena, chalcopyrite, pyrite, argentite, cerussite, covellite, limonite, and manganese oxides. Parisite constitutes 25 to 75 percent of parts of vein, and average is assumed to be 8 to 10 percent	------	Formation of vein interpreted by Kuzmenko to be due to hydrothermal activity, the rare earths having been concentrated in the residual solutions during differentiation of alkaline magma.

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