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GEOLOGIC SETTING OF THE

MOUNTAIN PASS RARE EARTH DEPOSITS

SAN BERNARDINO COUNTY, CALIFORNIA

by

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This ~~map~~ report is preliminary and has not been edited or reviewed for conformity with U. S. Geological Survey standards and nomenclature.

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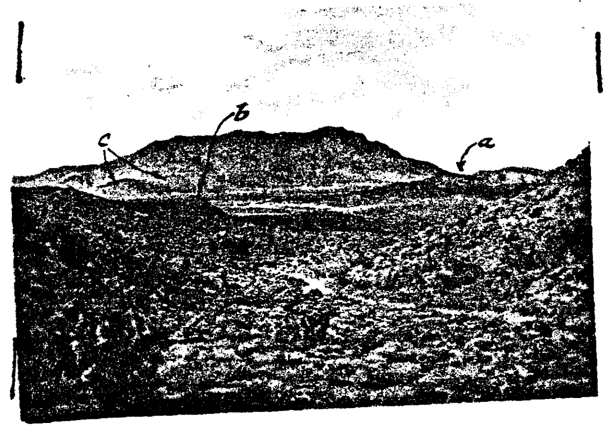

Plate 1.—Clark Mountain and Sulphide Queen mill (a) from shonkinite-syenite body northeast of Grover Spring. Knob (b) is potash syenite near Mexican Well. Scarp (c) indicates position of Clark Mountain fault.

Geologic setting of the Mountain Pass rare earth deposits, San Bernardino County, California

by J. C. Olson

ABSTRACT

The Mountain Pass district is in a block of pre-Cambrian metamorphic rocks bounded on the east and south by the alluvium of Ivanpah Valley. This block is separated from Paleozoic and Mesozoic sedimentary and volcanic rocks on the west by the Clark Mountain normal fault, and the northern boundary of the district is a prominent 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; pegmatites; and minor amounts of foliated mafic rocks.

The rare earth-bearing carbonate rocks are related to potash-rich igneous rocks, of uncertain age, that cut the metamorphic complex. The larger potash-rich intrusive masses, 300 or more feet wide, comprise one granite, two syenite, and four composite shonkinite-syenite bodies. One of the shonkinite-syenite stocks is more than a mile long. Several hundred relatively thin dikes of these potash-rich rocks range in composition, and generally decreasing age, from biotite shonkinite through syenite to granite. A few thin fine-grained shonkinite dikes cut the granite. These potash-rich rocks are cut by

east-trending andesitic dikes and by faults.

Veins of carbonate rock are most abundant in and near the southwest side of the largest shonkinite-syenite body. Although most veins are less than 6 feet thick, one mass of carbonate rock near the Sulphide Queen mine is 600 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 and parisite, quartz, and variable small quantities of crocidolite, biotite, phlogopite, chlorite, muscovite, apatite, iron oxides, fluorite, monazite, galena, allanite, sphene, pyrite, chalcopyrite, tetrahedrite, malachite, azurite, cerussite, wulfenite, aragonite, and thorite. The rare earth oxide content in most of the carbonate rock is less than 13 percent, but in some local concentrations of bastnaesite the content is as high as 40 percent.

The origin of the carbonate rocks and related potash-rich igneous rocks is considered in the light of similar associations of carbonate and alkalic rocks in Sweden, Norway, Russia, South Africa, and the United States. The carbonate rock may have originated (1) as a pre-Cambrian limestone or evaporite sequence in the gneisses; (2) by reaction between magma and the Paleozoic dolomite and limestone overlying the pre-Cambrian complex; (3) by alteration of pre-Cambrian gneisses by emanations from an unknown deep-seated source; or (4) by differentiation of an alkaline magma from shonkinite to syenite to granite, leading to a final carbonate-rich fraction, containing the rare elements, which was emplaced either as a concentrated or a dilute solution. The fourth hypothesis is considered the most plausible.

INTRODUCTION

Bastnaesite, a fluocarbonate of the cerium group of rare earth metals, was discovered in the Mountain Pass district in April 1949 by Herbert Woodward and Clarence Watkins while prospecting with a Geiger counter. Rare earths were detected in a sample of the rock, and bastnaesite indicated as the probable rare earth mineral, by E. T. Schenck of the United States Bureau of Mines, Boulder City, Nevada, and the identity of the bastnaesite was confirmed by D. F. Hewett of the United States Geological Survey. The district is a potential source of the rare earth metals and also contains barite, thorium, and minor quantities of other metals.

The rare earths are used in arc lamps, alloys of light metals and in steel, in tracer bullets, and because of their pyrophoric properties are used in the flints of pocket lighters and carbide lamps. Chemical compounds of rare earths have a wide variety of uses in industry. Uses in atomic research are suggested by the excellent absorption of slow neutrons by several of the rare earths. The rare earths have been obtained from monazite placer deposits in various parts of the world, chiefly from beaches in India and Brazil. A little bastnaesite was mined many years ago at Bastnäs, Sweden, and it has also been obtained from placer deposits in Belgian Congo. Bastnaesite also occurs near Corona, N. M.; Jamestown and near Pikes Peak, Colorado; Madagascar; and in the Ural Mountains.

During the period 1949-51, only a few tons of bastnaesite was mined at Mountain Pass for metallurgical tests. Only two mine workings in the district, the old Sulphide Queen gold mine and the Birthday shaft made in bastnaesite prospecting, are as much as 100 feet deep. Many pits and bulldozer excavations, commonly 5 to 10 feet deep, have been made in extensive prospecting for rare earth minerals.

Field work and acknowledgments

The Ivanpah one-degree quadrangle, _/ which includes Mountain

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_/ In process of publication by U. S. Geological Survey.

Pass near its center, was mapped by D. F. Hewett during the period 1924 to 1929. After the discovery in April 1949 of radioactivity and bastnaesite, an area of about 900 by 1,500 feet around the discovery, including the Birthday shaft, was mapped at 50 feet to the inch by W. N. Sharp and L. C. Pray between November 15, 1949 and January 20, 1950.

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, and additional information was obtained in subsequent short visits to the area. Aerial photographs were used in the field mapping, and the geology was transferred to planimetric which was compiled from the photographs by the Topographic Division, U. S. Geological Survey, Denver, Colorado.

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. Additional detail was added to this map and the area between it and the Birthday shaft area was mapped by D. R. Shawe during October, November, and December 1951.

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. In addition, a laboratory study of the minerals in the Sulphide Queen carbonate deposit was made by H. W. Jaffe during the period August 1951 to April 1952, and this investigation is still in progress.

Many geologists have contributed to the Mountain Pass investigations through field conferences, discussions, and laboratory assistance. Particular acknowledgment is made of the counsel and general supervision of D. F. Hewett, W. T. Pecora, W. C. Smith, and L. R. Page. Cordell Durrell made helpful suggestions concerning preparation of the report.

Prospectors and others in the district have given valuable assistance and information. Representatives of the Molybdenum Corporation of America, who have prospected extensively in the Mocam shaft and Sulphide Queen areas, have given close cooperation and valuable data.

Location and surface features

The Mountain Pass district is an area about 7 miles lond and 3 miles wide centered near Mountain Pass, a service station 60 miles southwest of Las Vegas on U. S. Highway 91, near the northeast corner of San Bernardino County (pl. 2). All parts of the district are readily accessible from the main highway by dirt roads. The district is 16 miles by paved highway west of Nipton, a station on the Union Pacific railroad. Altitudes range from about 4,000 feet at Wheaton Springs to slightly over 6,000 feet on Kokoweef Peak and the Mescal Range. Clark Mountain, just northwest of the district, dominates the terrain with an altitude of 7,903 feet. The surface east of Wheaton Springs slopes in a few miles to the floor of Ivanpah Valley, about 2,595 feet in altitude. Mountain Pass, with 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 gentle upland surface, about 5,000 feet in altitude, which has been referred to as part of the Ivanpah upland (Hewett, 1950). Remants of this surface have been found over large areas both east and west of Ivanpah Valley. 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 Ivanpah Valley. The central part of the district, near Mountain Pass, is a gentle surface 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 small fragments of the pre-Cambrian gneiss; Paleozoic limestone, dolomite, and quartzitic sandstone; Mesozoic sandstone and volcanic rocks; and igneous rocks, in various proportions depending upon their distances from the sources of these materials.

The climate is arid, but the district is dotted with juniper and joshua trees, and pines are found near the north end of the district and on Clark Mountain.

Regional setting

The Mountain Pass district is in a block of pre-Cambrian metamorphic rocks 4 to 5 miles wide and about 21 miles long in a north-northwest direction (Hewett, 1951). 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 occur. The area shown in plate 1, about 7 by 3 miles, includes all the known rare earth deposits and will be referred to as the district throughout this report.

The normal fault that bounds the district on the west has been traced for more than 20 miles and has been named the Clark Mountain fault by Hewett (1951). West of the fault lies the almost complete section of Paleozoic sediments, about 8,500 feet thick, and the complete section of Mesozoic rocks about 4,000 feet thick. The uppermost Mesozoic rocks include thick, dark red to brownish, volcanic flows and breccias that Hewett (1950) has reported to be chiefly dacitic in composition and probably Cretaceous in age, inasmuch as they rest upon sandstone correlated with the Jurassic Navajo sandstone. 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. Inasmuch as the Clark Mountain fault movement postdates the potash-rich intrusive rocks and the rare earth-bearing veins, the absence of these rocks west of the fault is attributable largely to the magnitude of the displacement.

The block of metamorphic rocks is bounded on the east by the Ivanpah fault, and the rocks east of it have been downfaulted at least

10,000 feet, largely in Pleistocene time (Hewett, 1951).

The northern limit of known rare earth mineralization is 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 north of it.

Several large, west-dipping 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 (1951) 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.

METAMORPHIC ROCKS

Pre-Cambrian rocks in the eastern Mojave region (See, for example, Hewett, 1931, pp. 10-11; Nolan, 1943, pp. 145-146; Hazzard and Dosch, 1936, pp. 308-309) have been divided generally into an older pre-Cambrian or Archean group of gneisses and schists with some granitic rocks, and a younger group of predominantly metasediments. There is no indication that any of the younger metasediments are present in the Mountain Pass district, and these gneisses and schists are therefore considered as probably older pre-Cambrian.

The pre-Cambrian metamorphic rocks, which underlie most of the Mountain Pass district, are well-foliated in contrast to the later intrusive rocks. Many varieties of metamorphic rocks are interlayered in various proportions in this complex. Distinct mappable units are few, but the complex was divided into units based upon relative proportions of the several types. Accordingly the contacts shown on the map of pre-Cambrian geology (pl. 3) represent gradations in relative proportions of heterogeneous rock types, rather than sharp changes in lithology.

Principal rock types

Among the rock types making up this complex are biotite gneiss and schist, garnetiferous in part; coarse-grained biotite-garnet sillimanite gneiss; hornblende gneiss, schist, and amphibolite, with varying amounts of biotite, chlorite, and augite; and quartz-mica schist. These banded or layered rocks, which are probably metasediments or metavolcanics in part, appear to be invaded by granitic gneisses of several types. One type, a biotite granite gneiss, has conspicuous rectangular to eye-shaped, commonly carlsbad-twinned, grains of potash feldspar as much as an inch long, in a fine-grained matrix of feldspar, quartz, and biotite. This biotite granite gneiss is strongly 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 type, a biotite-hornblende gneiss, occurs in small areas, for example about 2,900 feet N. 55° W. of the Windy prospects. It is older than the light-colored granitic augen gneiss and pegmatites and may be related to the biotite granite gneiss.

The most abundant rock type in the area is light-colored granitic augen gneiss, consisting chiefly of pink to white feldspar and quartz with very little of the dark minerals. The gneiss is fine-grained to pegmatitic, and adjacent layers vary in grain size. The dominant constituent is perthitic potash feldspar, which makes up about half the rock chiefly as augen of orthoclase or microcline. Plagioclase is markedly subordinate to the potash feldspar. 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. Minor muscovite or 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, but the feldspar augen are characteristic of the gneiss in most of the district.

A chloritic variety of the granitic augen gneiss contains pink or white feldspar augen which constitute 30 to 40 percent of the rock; quartz films and streaks, parallel to the foliation, 25 to 30 percent; and between the feldspar eyes, a greenish fine-grained mixture of chlorite, epidote, magnetite, hematite, and muscovite. Locally carbonate veinlets occur in late fractures. The feldspar is orthoclase chiefly with minor albite, and sericite or muscovite occurs as an alteration product of the feldspar. The chlorite and magnetite are probably derived largely from the alteration of biotite, but garnet present in some layers is also largely altered to chlorite.

Distribution of pre-Cambrian rock types

Unit E of plate 3 is composed chiefly of biotite granite gneiss, which occurs in large masses more than a thousand feet wide with only minor bands of other gneisses. These large masses grade outward into mixed gneisses in which many thin layers of the biotite granite gneiss, a foot or several feet thick, alternate in all proportions with bands of older layered gneisses such as hornblende gneiss and schist, biotite schist, and minor amounts of the younger granitic augen gneiss. The biotite granite gneiss in the thin dike-like bodies, most of which are concordant, is generally more schistose than that in the larger masses, and some of the thin bodies are finer-grained near their margins than in their centers.

Unit D, essentially a transition zone between E and C, is composed of the rocks of Unit E, together with the light-colored granitic augen gneiss which on the average constitutes less than half the total rock of Unit D, forming thin bands parallel to the foliation and, more rarely, cross-cutting dikes.

Unit C on the pre-Cambrian map consists dominantly of light-colored granitic augen gneiss in which are layers or larger irregular masses many feet thick of the hornblende gneiss and schist, biotite schist, and other rock types of Unit E. Some areas several hundred feet or more wide are almost entirely granitic augen gneiss, but in most places the rock is a migmatite containing thin layers of other gneisses permeated by granitic material. The individual bands of hornblende gneiss or schist, biotite schist, biotite-garnet gneiss, 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; hence it was not practical to delineate them at the scale of the district mapping. In 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 more abundant in Unit B.

Hornblende, biotite, and garnet are commonly altered to chlorite, and epidote is locally conspicuous in Unit C.

The rock described as chloritic augen gneiss is most abundant in Units D and C, chiefly as thin layers but also as the principal constituent of areas several hundred feet wide. 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 granite gneiss in zones which were much injected by later light-colored granitic augen gneiss.

Unit B on the pre-Cambrian map is characterized by coarse-grained or pegmatitic biotite-garnet-sillimanite gneiss containing abundant coarse granitic material in streaks along the foliation and in larger bodies. Like the other units, Unit B is variable and contains bands of various other layered metamorphic rocks. It is separated from Unit C chiefly because of the coarser grain size and the more widespread occurrence of sillimanite in Unit B. Garnet and biotite grains are as much as an inch in diameter. Foliation is well-developed but irregular in detail owing to many small folds and crenulations. Because of the metamorphism, and the impregnation by granitic material, the ultimate origin of the coarse-grained gneiss is obscure. The layering, and the 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. For example, garnet is localized in pegmatitic granite gneiss within a few feet of a mass of garnet-biotite-sillimanite gneiss, but the same rock in a large area away from the inclusion contains virtually no garnet.

Pegmatites

Granitic pegmatites of simple composition occur in many parts of the district. Some are as much as 125 feet wide and some are more than 1000 feet long. Some of the largest are shown on the geologic maps (pls. 1 and 3). They consist of pink to white potash feldspar and quartz, with minor gray to white plagioclase, muscovite, and garnet. Zoning or 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 in color of the potash feldspar, which locally is pink in the pegmatite as opposed to white potash feldspar in the granitic gneiss. The pegmatites are commonly somewhat gneissose, and have taken part in pre-Cambrian metamorphism.

Mafic rocks

Hornblende gneiss, schist, and amphibolite occur in many parts of the district, and rocks of more mafic composition, such as peridotites, are known. Some of the layered hornblendic rocks are probably of sedimentary or volcanic origin, as mentioned above, but others which occur in small oval patches or dike-like bodies are probably intrusive into the banded gneisses. Some of these mafic rocks are cut by thin dikes of the granitic gneisses, but some ~~are probably later as some~~ mafic gneisses contain broken fragments of granitic gneiss, and pegmatite appears to be cut by at least one hornblende gneiss band. For example, one northeast-trending pegmatite, which cuts across the foliation of biotite granite gneiss, is in turn cut by a northwest-trending dike of hornblende gneiss in which the foliation is essentially parallel to that of the biotite granite gneiss.

The mafic rocks are both fine- and coarse-grained, and are locally recrystallized near thin dikes of granitic gneisses. Many are dioritic in composition, containing hornblende and plagioclase with minor augite, quartz, and sphene. Thin sections were made of two well-foliated bodies of serpentinized gabbro or peridotite, composed of about 30 to 35 percent clinopyroxene, 40 to 45 percent serpentine, with olivine, opaque minerals, and minor chlorite, muscovite, and spinel. Serpentine appears to have formed from both olivine and the clinopyroxene. Many of the 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 of the metamorphic rocks

Unit E, which contains only minor amounts of the granitic augen gneiss, is bounded on both sides by migmatite or injection gneiss of units C and B containing greater amounts of the granitic augen gneiss. Unit D is a transitional zone, containing about 10 to 50 percent granitic augen gneiss, between E and C or B. Unit E is thought to be a pendant of older gneisses in which, generally speaking, there was relatively little permeation by granitic material to form migmatite. The introduction of granitic material was least in this pendant, greater in Units D and C, and was greatest in Unit B where coarse pegmatitic gneisses with sillimanite are found. This pendant (unit E) is displaced by faults, seems to thin southward, and was not delineated south of the cross-fault that branches southeastward from the Clark Mountain fault. Although some of the rocks south of this fault are probably related to the biotite granite gneiss of Unit E, they are so intermixed with the granitic augen gneiss that it was not practical to separate them.

The largest pegmatites are found chiefly in the areas of mixed rocks between Unit E and Unit C. This occurrence of the pegmatites harmonizes with the interpretation of Unit E as a pendant of older gneisses surrounded by the predominantly granitic gneisses of Unit C, as pegmatites are expectable in injection zones marginal to the migmatite and granite gneiss areas.

All the pre-Cambrian 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. The foliation dips 50° to 80° W. in much of the area. Local deviations from the general trend were noted, for example 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 of coarse-grained biotite-garnet-sillimanite gneiss designated as Unit B.

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 drag folds plunging 40° N, are abundant in a zone 30 to 40 feet wide, in the pegmatitic garnet-biotite gneiss about 6,000 feet N 56° E of Mexican Well This zone parallels the regional foliation and is cut by an east-trending andesitic dike (Tertiary ?) that is not displaced

Within a few feet of most of the faults, 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, 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 seems to increase 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 plunges generally in a direction a little south of west, almost down dip, commonly at angles of 55 to 70 degrees 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 appears to have developed during the deformation and metamorphism of the region, at least part of which occurred after all the pre-Cambrian rocks were emplaced The foliation and lineation were very likely not all produced simultaneously, but the metamorphism was long continued, and the degree of metamorphism varied at different places and times For example, many pegmatites appear to have been injected along a pre-existent 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 appear to cut across pegmatites and granitic augen gneiss and these, too, have a foliation approximately parallel to that of their wall rocks even though the bodies are discordant to this foliation.

Variations in the metamorphic rocks 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 in such layers, whereas nearby layered gneisses if not quite so mobile might escape much of the deformation that produced the augen gneisses Similarly, the crenulations and the coarse grain size of the sillimanite-bearing gneisses imply different conditions, perhaps greater temperature or pressure, in their formation than in the more evenly layered gneisses in other parts of the district

INTRUSIVE ROCKS

The essentially non-foliated intrusive rocks that cut the pre-Cambrian metamorphic complex comprise two general types: (1) shonkinite, syenite, granite, and other potash-rich dike rocks of composition intermediate between them, most of which trend northwest, and (2) andesitic to rhyolitic (felsitic) dikes, most of which trend east. The potash-rich intrusives postdate the pre-Cambrian foliation and antedate the Tertiary (?) andesitic dikes and some of the faults in the district. Possibly they are late Mesozoic, like certain other intrusive and extrusive rocks in the region, but their age has not been definitely established. The potash-rich rocks range in composition from biotite shonkinite and fine-grained lamprophyric shonkinite (minette) through hornblende and biotite syenite, potash syenite, to granite. Many intermediate and closely related types could no doubt be distinguished in a thorough petrographic study.

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, pp. 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, etcetera, may be present in small quantities". Although the type shonkinite of the Highwood Mountains contains minor nepheline, the feldspathoid is not an essential constituent as defined by Weed and Pirsson, and the term is used here in its broad sense as a syenitic rock with more than 50 percent dark minerals. Later detailed petrographic studies of the type shonkinite in the Highwood Mountains have been published by Barksdale

(1937), Larsen and Buie (1938) and by Larsen, Hurlbut, Buie, and Burgess (1941).

The dark mineral content of the shonkinite of the Mountain Pass district is rarely as much as 70 percent and is more commonly near 50 percent. Biotite-rich syenites with 30 to 50 percent mafic minerals are also common. The most abundant dark mineral is biotite, which occurs in relatively coarse flakes as much as 0.5 inches in diameter and constitutes 25 to 40 percent of most of the shonkinite; hence the rock is a biotite shonkinite. Most of the biotite is black to dark red-brown, but some flakes or parts of grains are green. The biotite is commonly dotted with iron oxides, as seen in thin section, and pleochroic haloes are present but not abundant. Small flakes of biotite are commonly enclosed poikilitically in the coarse- to medium-grained potash feldspar. In porphyritic shonkinite the biotite occurs as phenocrysts and in the groundmass. Locally, the biotite flakes tend to lie parallel to one another, but in nearly all the shonkinite the biotite flakes have random orientation, imparting rough glistening surfaces on weathering of the rock.

Amphibole and pyroxene are next to biotite in abundance and constitute 5 to 30 percent of the shonkinite. Common hornblende and augite predominate among the minerals of these groups, but aegirine and soda-amphiboles such as riebeckite and arfvedsonite are widespread. The clinopyroxenes augite and aegirine occur, together or separately, 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, and broken crystals cemented by mixtures of potash feldspar, biotite, and iron oxides. Augite crystals commonly are zoned parallel to crystal outlines. Some coarse grains of hornblende have cores of augite.

The hornblende occurs as individual grains, mostly 0.25 inches or less in length, or as aggregates of small grains. The amphibole is common hornblende in some of the rocks, soda-amphibole in others, and commonly both types are present. The sodic amphiboles occur both as coarse individual grains among the other constituents and in fibrous form, commonly marginally replacing grains of common hornblende or pyroxene. 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. The soda-amphiboles are characterized by pale bluish and greenish pleochroism. Not uncommonly the pleochroism varies along the length of the grain, suggesting variations in soda content.

The amphiboles and pyroxenes in three shonkinite samples were examined by Robert S. Jones, from whom the following data were obtained: In these three samples the major dark mineral, except biotite, is monoclinic amphibole with pleochroic colors that indicate hornblende and riebeckite. The indices and color of the hornblende range from N_x 1.625, yellowish green to light yellowish green, to N_z 1.695, dark green to light yellowish brown. The birefringence ranges from 0.005 to about 0.020. The birefringence of the riebeckite is about 0.005, color blue to violet, and the indices range from N_x 1.665 to N_z 1.695. Intermediate colors between those given above can be accounted for by isomorphic mixtures between hornblende and riebeckite. 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. Aegirine was present in one of the three samples, but was less abundant than the riebeckite.

The potash feldspar, which makes up nearly half of the shonkinite, generally occurs in anhedral grains 0.1 to 0.5 inches in diameter, typically enclosing biotite or, less commonly, hornblende needles or pyroxene prisms. Finer-grained potash feldspar occurs in the groundmass of some shonkinite with coarser biotite or augite phenocrysts. 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. In one thin section, aggregates of potash feldspar, sericite, and calcite, roughly hexagonal in outline, suggest possible pseudoleucite.

Generally speaking, shonkinite, syenite, or granite that contains soda-amphibole also contains microcline; conversely, thin sections that do not show the scotch-plaid twinning characteristic of microcline generally have no soda-amphibole. Of 25 thin sections of shonkinite, syenite, and granite examined to check this relationship, 14 contain microcline; eight of these also contain soda-amphibole and/or soda-pyroxene, and 5 of the other 6 contain no amphibole or pyroxene. The other eleven sections contain no potash feldspar with the characteristic microcline twinning; of these, 5 contain augite or common hornblende, but not the soda-rich varieties, and the other 6 contain no amphibole or pyroxene.

Accessory minerals in the shonkinite comprise sphene, leucoxene, zircon, allanite, epidote, monazite, olivine, and locally as much as 5 percent apatite or iron oxides. The accessories are commonly localized around and in the mafic minerals.

The shonkinite, in common with other members of the syenitic suite of rocks at Mountain Pass, is characterized by textural variability. The rock is mostly medium-grained, but ranges from fine to pegmatitic, and 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, which are more felsic than the enclosing shonkinite, potash feldspar predominates as a general rule and mafic minerals are subordinate. Soda-amphibole and aegirine are the common mafic constituents of the pegmatite, and sphene, zircon, allanite, and biotite are locally present. Porphyritic shonkinite, in which chiefly biotite and some augite or hornblende occur as phenocrysts, is common, and in some of the porphyritic shonkinite these dark minerals occur in both the phenocrysts and the groundmass.

The shonkinite is altered in many places, with the development of such secondary minerals as carbonates, chlorite, epidote, sericite, hematite, and quartz. One type of alteration, conspicuous near carbonate veins, consists of the replacement of the shonkinite minerals by calcite in irregular patches, veinlets of calcite and quartz, development of sericite from potash feldspar, and a loss of color and pleochroism from the biotite, associated with opaque yellow veinlets and dark spots of iron oxide apparently derived from alteration of the biotite.

Dark green chlorite-rich dikes occur in several areas near the Clark Mountain fault, 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 and/or microcline microperthite ranges 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 rare but in places makes up as much as 15 percent of the rock, and there are minor quantities of iron oxides, apatite, sphene, epidote, and allanite.

Syenite

The syenite includes feldspar-rich rocks that have less than 50 percent mafic minerals and less than 5 percent quartz. 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. Quartz forms 0 to 5 percent of the syenites, 5 to 10 percent of quartz syenite, and more than 10 percent of the granite. Accessory minerals that occur in variable small amounts are iron oxides, apatite, sphene, zircon, rutile, and allanite. Metamict thorite (?) is present in one thin section as an orange-brown mineral of mottled appearance, high relief, and low birefringence.

Much of the syenite is equigranular and relatively coarse-grained (0.1-0.3 inches). In some porphyritic types the orthoclase occurs both as rectangular phenocrysts and in the groundmass. The more mafic syenites, with 25 to 50 percent dark minerals, have biotite, amphibole, or rarely pyroxene as phenocrysts, whereas the porphyritic leucosyenite and granite have phenocrysts of potash feldspar. Syenite pegmatite occurs as irregular patches locally in shonkinite and syenite.

The potash feldspar, which forms the greater part of the syenite, is partly orthoclase, partly microcline, or mixtures of the two; perthitic intergrowths 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. In one thin section, several perthitic orthoclase grains have strongly sericitized oval cores rimmed by relatively unaltered feldspar. The marginal feldspar extinguishes simultaneously with some of the cores but not with others, suggesting stages during crystallization of the feldspar.

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 granitic 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; for example, in one thin section of the contact of a 3-inch dike of syenite in shonkinite, the riebeckite in the syenite is more abundant near the contact than the middle of the dike. The fibrous soda-amphibole, called crocidolite in this report, 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 is common in some of the syenite. For example, a thin section of syenite from the composite intrusive northeast of Grover Spring, composed chiefly of perthitic microcline and orthoclase, contains both aegirine and soda-amphibole. The aegirine is pale yellow-green and weakly pleochroic in section. The soda-amphibole (riebeckite?), which is pleochroic in blue and violet, appears to have formed in part by replacement of aegirine with which it is closely associated.

Near carbonate veins the syenites, like the shonkinite, are conspicuously altered, with sericitization of the feldspar; alteration of the biotite to a reddish-brown or bleached color with development of iron oxide spots; much calcite as veinlets, fine grains replacing feldspar, and selectively replacing mafic minerals; quartz veinlets; and introduction of pyrite. Plagioclase, which makes up less than 10 percent of the feldspar in one section of the altered syenite, is relatively clear and well-twinned in contrast to the much-sericitized potash feldspar, suggesting it was introduced or recrystallized.

Where alteration is especially prominent, as near faults or veins, the potash feldspar is strongly sericitized and the mafic minerals of the syenite are altered. Chlorite and chlorite-calcite-magnetite intergrowths are pseudomorphous after biotite, and aggregates of iron oxide and carbonate take the place of former pyroxene or amphibole grains.

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 lavendar, or pink, to a dark red on weathered surfaces of the granitic intrusive on Mineral Hill. The thin dikes, shown on the map 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. The granites range in grain size from fine to coarse. The larger intrusives 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. Some of the potash feldspar is partially altered to muscovite or sericite. Grains of albite or oligoclase constitute 5 to 10 percent of the average granite, rarely as much as 15 percent. Micrographic textures are present but uncommon.

The sparse dark minerals, which generally make up less than 5 percent of the granite, comprise biotite, hornblende, soda-amphibole (riebeckite?), and rarely aegirine or aegirine-augite, essentially the same mafic minerals as in the syenite and shonkinite but in minor quantity. Accessory minerals include iron oxides, zircon, apatite, sphene, monazite, thorite (?), and allanite.

Local alteration of the granite, particularly near carbonate veins, is evidenced by the replacement of feldspar and mafic minerals by calcite, veinlets of calcite or dolomite with minor barite, and veinlets or blebs of quartz. Fluorite is not uncommon as a minor constituent in small grains or in veinlets. Aggregates of riebeckite, fluorite, iron oxides, biotite, and chlorite in one thin section appear pseudomorphous after pyroxene grains. Minor chlorite and fibrous soda-amphibole replace biotite and hornblende, respectively, and some pyroxene grains are altered to aggregates of limonite, calcite, and chlorite.

Fine-grained biotite shonkinite

Several dikes of fine-grained biotite shonkinite cut the shonkinite, syenite, and granite. They are similar in composition to the shonkinite in the larger masses but are generally porphyritic, with phenocrysts of biotite, or rarely other mafic minerals, in a fine-grained holocrystalline groundmass. The typical fine-grained shonkinite is composed of 30 to 50 percent orthoclase and microcline, light brown biotite as the dominant mafic mineral, subordinate fine amphibole needles and clinopyroxene, sodic plagioclase, and minor calcite, iron oxides, apatite, and fluorite. The amphibole and pyroxene are, at least partly, the sodic varieties riebeckite and aegirine. The fine amphibole occurs largely in a felt of randomly oriented needles in the groundmass, but some amphibole fibers are arranged radially as though replacing an earlier mineral. Some aggregates of epidote, calcite, and biotite probably represent former grains of augite. The feldspar, which constitutes most of the groundmass, is in anhedral grains mostly 0.5 to 1 mm in diameter. Flow structure, due to the parallel orientation of biotite flakes, is conspicuous near the walls of some dikes but less so toward their centers.

Areal distribution

The potash-rich dike rocks occur in a belt about $1\frac{1}{2}$ miles wide, from the transverse fault, about 2,000 feet northeast of Mohawk Hill, at least as far south as the limit of geologic mapping, a distance of about 7 miles in a northwesterly direction. 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 two or three miles between the southern map boundary and the alluvium of Ivanpah Valley. Within the district seven larger 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 intrusives, especially those containing quartz, are relatively resistant to weathering and stand out as ridges and peaks. The biotite-rich dark intrusives, however, are more friable than the other rocks, crumble relatively easily on weathering, and commonly form areas of low relief. 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 tabular bodies, in general parallel with the foliation in the gneiss, and they are concentrated near the 7 larger intrusive bodies. On the average, the thin dikes, whether of shonkinite, syenite, or granite, are finer-grained than the same rocks in the stocks, and porphyritic varieties are abundantly represented in the dike rocks.

Most of the thin dikes are essentially homogeneous throughout their extent, but a few are composite. For example, about 3,800 feet N. 85° W. of the Windy prospects, a nearly vertical composite dike 6 to 9 feet thick, exposed for a length of 50 feet, 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 lower half of this dike is light-colored biotite syenite, and the upper half is a slightly younger injection of finer-grained quartz-bearing leucosyenite.

Inclusions of older rock are less common in the thin dikes than in the 7 larger intrusive bodies, but are found occasionally. For example, about 5,500 feet S. 54° E. of the Highway Maintenance Station, a fairly fine-grained biotite-rich syenite or shonkonite dike, 6 feet thick, cuts sharply across the pre-Cambrian foliation and has flow structure parallel to the contacts. Near the center of the dike are several slab-like inclusions of granitic augen gneiss a foot or less thick, in which the foliation is parallel to that of the gneiss wall rocks but at an angle to the attitude of dike and inclusions. The dike is cut by many calcite veinlets, some with purple fluorite.

Composite shonkinite-syenite stock 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 about 6,300 feet long and 1,800 feet in maximum width. The long dimension of this mass is N. 65° W., discordant to the general trend of the pre-Cambrian foliation which is variable near the intrusive but probably averages about N. 20° W. The irregular intrusive contacts dip southwestward at angles mostly of 25 to 70 degrees, but in several places the contact is formed by steeply dipping faults trending about N. 60-70° W.

The stock is composed chiefly of shonkinite which grades into irregular, small, erratically distributed masses of hornblende or biotite syenite, or pink syenite composed of 80 percent or more microcline, some biotite, and a little amphibole or pyroxene, that are not differentiated on the map of the district. Many contacts between shonkinite and syenite are gradational, but some are sharp. Locally, small shonkinite fragments are enclosed in syenitic matrix.

The shonkinite-syenite complex is cut by many dikes of generally finer-grained granite, pink fine-grained syenite, and a few dark fine-grained dikes of shonkinitic composition. The later dikes, like many of the carbonate veins, appear to have been emplaced in fractures in the shonkinite-syenite mass and adjacent pre-Cambrian gneiss, because of their parallelism in certain areas, sharp angular intersections of segments, generally fine grain, and sharp contacts that locally have relatively fine-grained chilled margins. Most of the dikes are a few feet or a few inches in thickness, but exceptionally they are as much as 200 feet wide. They are nearly vertical or dip steeply south or southwest on the average. The largest and most abundant dike rocks are granite and fine-grained pink syenite. About half a dozen dikes of fine-grained shonkinite have been mapped, the largest of which is about 1,000 feet long and 10 to 30 feet wide. The dark fine-grained shonkinite dikes cut the granite dikes in several places, indicating their relatively late age.

Local alteration of the shonkinite, especially prominent near some carbonate veins, yields a light-colored rock in which the biotite is altered to a pale reddish-brown or nearly colorless mica; calcite is abundant as fine grains selectively replacing some grains that may have been amphibole, pyroxene, or plagioclase, or as veinlets with minor quartz; and the microcline is locally altered or replaced by sericite and calcite. A little pyrite has been introduced into the wall rocks adjoining some carbonate veins.

A few small inclusions of gneiss, 10 to 20 feet across, occur within the shonkinite. Along many of the intrusive contacts a breccia zone perhaps 10 feet thick occurs in which fragments of pre-Cambrian gneiss are enclosed in and partly replaced by syenitic or shonkinitic material. Some of the gneiss fragments, in which the foliation is still discernible, contain crystals of potash feldspar, in part zoned and having cores of slightly different color than the rims, that appear to have grown in the gneiss fragments and imparted to them some of the features of the syenite or shonkinite. One of the late fine-grained shonkinite dikes, at least 400 feet inside the shonkinite-syenite stock, contains numerous small slab-like inclusions of gneiss.

Near the contact about 1,000 feet east of the Sulphide Queen mine the stock consists of a complex assemblage of shonkinite, dark biotite or hornblende syenite, pink biotite or hornblende syenite with only minor dark mineral, pink leucosyenite, quartz syenite, and granite. Although impractical to map in detail at the scale of the district mapping, these small irregular masses show a sequence of intrusion in order of decreasing basicity. In this part of the intrusive body, relatively coarse-grained biotite shonkinite occurs in a thin zone along most of the contact, and numerous fragments of it are included in quartz syenite and granite. Inch-thick dikes of lighter-colored syenite cut darker-colored 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 or reconstituted from the pre-Cambrian gneiss.

Shonkinite-syenite bodies northeast of Grover Springs

Northeast of Grover Spring are two composite shonkinite-syenite bodies separated by about 400 feet of pre-Cambrian 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 the northwestern about 1,250 feet long. 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 intrusives and generally parallel the foliation.

The general distribution of the three principal rock types making up these two shonkinite-syenite intrusives is shown in plate 4. The biotite shonkinite is composed generally of 50 percent or more biotite and pyroxene, about 5 percent fibrous blue soda-amphibole, and the remainder largely pink orthoclase. This rock ranges from fine- to coarse-grained, but is somewhat finer-grained on the average than the lighter-colored syenites in this intrusive body. Irregular masses of the biotite shonkinite occur near the contacts with gneiss, as shown on the map, and small masses too thin to show at this scale form a discontinuous zone 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 nearby syenite dikes, demonstrating the shonkinite to be the oldest type in the composite intrusives.

Most of the southern half of the southeastern intrusive is composed of mafic syenite (see pl. 5A), 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 pink potash feldspar. The grain size is medium to coarse, but locally becomes somewhat finer within about a foot of the contact with the shonkinite.

The greater part of the two intrusive bodies northeast of Grover

Spring consists of more felsic syenite, containing less than 5 percent biotite on the average, about 5 to 15 percent blue amphibole and clinopyroxene, and the remainder pink, orange, or flesh-colored potash feldspar. The rock is almost invariably a shade of red because of the high potash feldspar content and abundant iron oxide stains. Contacts between this red 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 occur in 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 dike-like 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 dike-like 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 intrusives. The pegmatite consists largely of potash feldspar with both fibrous and coarsely crystalline blue amphibole, aegirine, and very little biotite. 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 disturbed locally near the shonkinite-syenite bodies.

At the south end of the southeastern intrusive body, the granitic augen gneiss within 100 feet of the contact is cut by many small dikes of syenite and granite. Near these dikes, the pre-Cambrian gneiss is partly replaced by syenitic material, potash feldspar grains having developed in the gneiss. Some of the syenite near this contact is composed of 50 to 85 percent microcline and microcline perthite, which occurs in subangular grains that are partly light and partly dark gray in hand specimen. In thin section, the dark portion, which commonly forms a border around a relatively clear core, is found to be potash feldspar with the same optical orientation but crowded with many dusty opaque particles, probably hematite. Coarse grains of this microcline are separated by interstitial quartz with minor opaque minerals, hematite, amphibole, and biotite which form 0 to 25 percent of 4 thin sections of these rocks. One of the specimens has a gneissic structure like that of the pre-Cambrian granitic gneiss. Other minerals that constitute a fraction of a percent to 5 percent of

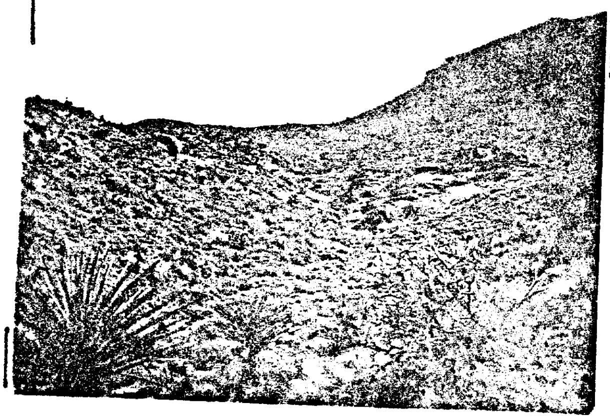

Plate 5A.—Rounded outcrops of syenite and mafic syenite northeast of Grover Spring.

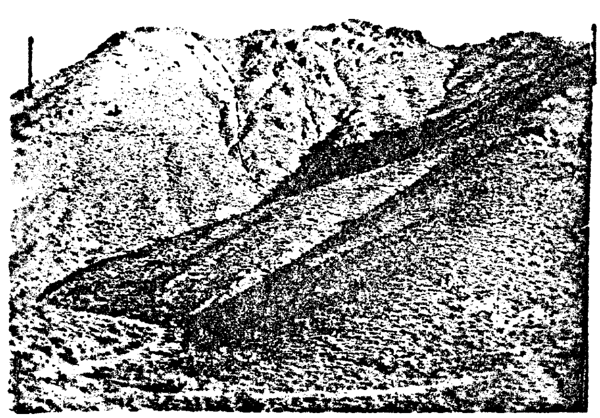

Plate 5B.—Granite of Mineral Hill, from west. Dashed line indicates approximate contact between granite (on ridge) and surrounding pre-Cambrian gneisses and pegmatite.

the 4 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 stock southeast of Highway Maintenance Station

The composite shonkinite-syenite stock 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 stock, occurring along the northeast side of the body almost throughout its extent. Pink syenite makes up most of the remainder of the body, mainly along its southwest side and as small dikes or pods in the shonkinite. The pink syenite is mostly potash feldspar, with a very few percent of amphibole and pyroxene. Dikes of granite, 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. Veinlets of carbonate 0.1 to 0.3 inches thick, and of the fibrous blue amphibole crocidolite, are common.

The irregular northeastern contact of the intrusive body appears to dip about 50° SW. on the average. The southwest contact is partly a nearly vertical fault and partly an intrusive contact with the pre-Cambrian, which is dominantly granitic augen gneiss. In places near the syenite or shonkinite the gneiss is impregnated with feldspathic material. In one place near the south contact, pre-Cambrian gneiss is brecciated, and small gneissic fragments, 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.

Two thin sections were made of rocks, near the northeast contact of the intrusive, that megascopically appear to be impregnated by feldspar and quartz from the intrusive but retain some of the gneissic structure. In thin section these 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 stock contain occasional blebs or pockets of quartz, commonly with specular hematite, similar to those associated with the other intrusives south of U. S. Highway 91.

Potash syenites near Mexican Well

Two potash-rich leucosyenites occur within half a mile of Mexican Well, one southwest of it and the other southeast. The intrusive 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 the intrusive is finer-grained and local patches contain quartz, partly in euhedral terminated prisms, in amounts up to as much as 20 percent of the rock.

The potash syenite body southwest of Mexican Well is about 600 by 750 feet in plan. It 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 a fibrous dark blue amphibole or as 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 owing to 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 intrusive body on Mineral Hill (see pl. 5B) is a composite of red granite, biotite syenite, and leucosyenite. The dark minerals range from almost none to 20 percent of the mass. Biotite is the most common dark mineral, but amphibole is also prevalent. The percentage of quartz ranges from 35 to 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, zircon, allanite, and rare thorite (?).

The northeast (footwall) contact of the granite body 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 discordent 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 pre-Cambrian gneiss 40 feet or so in diameter are generally oriented parallel to the foliation of the gneiss wall rock, but smaller blocks of the order of 3 feet in diameter have been rotated to any angle. Contacts are so gradational that in places it is difficult to draw a sharp line between intrusive 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, reddening of the rock, and iron oxide staining along fractures. Inward toward the granite intrusive, 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 wall rock, but the inclusions are but little rotated until they are of the order of a foot to three feet in diameter. The proportion of granite increases inward, until it predominates over the many small inclusions with random orientation. The inclusions are locally enriched in feldspar, the quartz in them redistributed, and the dark minerals altered. Centrally from the 200-foot zone of mixed rock the inclusions are fewer, and they are practically absent from 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, and uncomplicated by inclusions or apophyses. Along some contacts the gneiss shows but little evidence of alteration, such as iron staining and small quartz veins and vugs.

Within the intrusive body, a sequence of formation of the syenitic and granitic rocks is indicated by inclusions of one in another and by relatively siliceous dikes cutting less siliceous rock. Angular or irregular quartz-poor inclusions, perhaps 10 or 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. These gradations suggest that the inclusions and the rock that encloses them formed near one another in space and time, under conditions that permitted relatively free transfer of material between them. Some thin dikes, however, cut the main intrusive with sharp contacts. 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 as fragments 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 granitic dikes intrude the gneiss surrounding the red granite intrusive, commonly as a web of many thin branching dikes. Some of these are apophyses of the main mass, but others cut both the intrusive body and the gneiss. One offshoot of granite diminishes in thickness and grain size away from the main mass, and contains some inclusions of wall rock with sharp boundaries.

Quartz veins, rarely as much as 2 feet thick, cut the granite and adjoining gneiss. Quartz and specularite occur as blebs and lining drusy cavities, commonly 1 to 3 inches in diameter, near the margins of the granite intrusive 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 that is light brown in powder, probably siderite chiefly. Apparently after consolidation of the granite, solutions corroded it and the nearby gneiss, and deposited quartz and specularite.

Small patches of granite or quartz syenite pegmatite, commonly an inch or two 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.

Contacts

Local contact metamorphism, restricted to pre-Cambrian gneisses near the potash-rich igneous rocks and carbonate rocks, has been mentioned in the descriptions of the 7 shonkinite-syenite-granite bodies. These contact alterations have not been studied in detail petrographically, but certain features have been noted that suggest the local development of contact rocks by a process akin to the fenitization of Brögger (cf. Brögger, 1920; Von Eckermann, 1948; Adamson, 1944; Dixey, Smith, and Bisset, 1937½; and others listed in bibliography).

Locally near the contacts of the Mountain Pass intrusive bodies the quartz is recrystallized and redistributed, converting some gneisses to quartz-poor syenitic rocks, and forming small blebs, veinlets, and irregular pods of quartz, commonly without wavy extinction, in others. The rocks are locally reddened, chiefly through disseminated hematite and iron staining along fractures. Microcline grains have formed along foliation planes in the gneiss, tending to obliterate the foliation. Microcline perthite grains are commonly 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 albite are found among altered and sericitized potash feldspar grains, as though recrystallized or introduced. 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. 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.

Genetic sequence

The sequence of intrusion of the igneous rocks is the same throughout the district, as illustrated by examples from the various 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, pink syenite and granite. Dark dikes of shonkinite, finer-grained on the average than the shonkinite of the larger stock, cut the granite and are the youngest of the potash-rich rock sequence wherever the age relations are clearly established. The relation of carbonate rocks to the dark 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 and hence are younger than all the potash-rich intrusive rocks.

Age

The potash-rich dike rocks are essentially nonfoliated, cut across the pre-Cambrian foliation, and are cut by the Tertiary (?) andesite dikes which were emplaced in fractures. The potash-rich rocks may be any age from pre-Cambrian to Tertiary. Most of the faults shown on the geologic map are younger than the potash-rich igneous rocks, but some faults with similar trends apparently controlled in part the shonkinite-syenite-granite intrusives. 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 pre-granite structure is roughly paralleled by the later andesite dike swarms. Another example is the northwest-trending fault zone that crosses the large carbonate body near the Sulphide Queen mine, which is later than the carbonate rock but is itself silicified and mineralized probably late in the same period of calcite-barite-bastnaesite mineralization. This suggestive relationship to periods of faulting in the district makes a late Cretaceous or Tertiary age of igneous activity plausible but uncertain.

Volcanic rocks of probable Cretaceous age occur in the Mescal Range south of Mescal Spring. A correlation between those volcanic rocks and the potash-rich dike rocks is possible but not proved, as the volcanic rocks were not studied in detail in this investigation. According to Hewett (1950) these volcanic flow breccias are mainly dacitic in composition. They rest on Jurassic sandstone and, on the west, are overridden by Paleozoic sediments along the Mescal thrust. The volcanic rocks are downthrown 10,000 to 12,000 feet along the Clark Mountain fault, relative to the gneisses east of the fault. The original position of the volcanic rocks before faulting must have been nearly above the granite of Mineral Hill, as shown in cross-section B-B' (pl. 8) through the volcanic rocks and the granite of Mineral Hill. Therefore the granite, and possibly other intrusive bodies in the district, may represent conduits for the Cretaceous volcanic materials, but this is merely a possibility and is by no means proved.

Other igneous rocks of Cretaceous or early Tertiary age are known in this region. For example, porphyritic orthoclase-rich dike rocks (granite porphyry) in the Goodsprings district are thought by D. F. Hewett (1931, pp. 36, 38, 54-55) to have been intruded in late Cretaceous or early Tertiary time, probably the latter. Hewett (1931, pp. 38-39) also describes lamprophyre dikes, complementary to the granite porphyry dikes and also intruded in the same epoch, preceding ore deposition, from 3 localities in the Goodsprings quadrangle. In the southwestern part of the Ivanpah quadrangle, near the south end of Old Dad Mountain, Hewett (1951) has mapped a large body of granite that intrudes flow breccias somewhat like those in the Mountain Pass district. This granite is relatively rich in potash and thus more closely resembles the syenite and granite at Mountain Pass than any other known in this region.

Lamprophyres and acidic dikes of the Searles Lake quadrangle are reported to be pre-middle Miocene and post-lower Cretaceous, probably early Eocene in age (Hulin, 1934). 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. Hopper (1947, p. 413) tentatively correlates these with the similar Eocene(?) dikes of the Searles Lake Quadrangle described by Hulin. Alkalic syenite and melanite-nepheline syenite, cutting Paleozoic dolomite in the northern Panamint Range, have been described by McAllister (1940).

Andesite and rhyolite dikes

Dike rocks ranging from basalt to rhyolite, but generally andesitic in composition, trend eastward in contrast to the northwesterly trend of the potash-rich dikes and the pre-Cambrian foliation. These dikes are younger than the potash-rich dike rocks, which they cut, but older than some of the faulting. They are probably Tertiary, like other similar dike rocks in the region. The andesitic and rhyolitic dikes range from about 1 to 20 feet in thickness, and some are more than a mile in length.

The andesitic dikes vary considerably in composition and texture. Many are dense fine-grained rocks, dark green or gray in color; black, brown, buff, or pinkish shades are also found. The range in composition is no doubt greater than the name implies, as some are basaltic, although most are probably andesitic. Only a few of these dike rocks have been studied in thin sections. Andesine is the chief constituent and makes up about 60 percent of the rock, as small lath-shaped phenocrysts about 1 mm long and in the groundmass. Light brown pleochroic hornblende, with extinction angle of 20 degrees, makes up about 20 percent of one section, occurring both in phenocrysts and groundmass.

Augite constitutes about 5 percent of another section. Opaque minerals make up 1 to 5 percent of the rock. Rarely quartz is present in small round grains. The andesite is 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 formerly glassy groundmass. Porphyritic varieties, having phenocrysts of plagioclase, hornblende, or augite, are not uncommon, and spherulitic texture was found locally.

The andesite dikes occur in four main areas or swarms. Within these swarms 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 dike swarms were emplaced in fractures. Some of the fractures are pre-andesite, with obvious though probably small displacement shown by the offset of pre-Cambrian units or potash-rich dike rocks. Most of the dikes are nearly vertical, but a few thin bodies have dips as low as 40 degrees. 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 andesitic dikes were not observed in the sediments immediately west of the Clark Mountain fault, even though many of the dikes in the pre-Cambrian area appear to intersect the fault, suggests that some post-andesite movement has probably occurred on the Clark Mountain fault.

About half a dozen rhyolite dikes were distinguished from the andesitic group, to which they are probably 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 in color, and, like many felsitic dike rocks, it commonly has a flow structure or sheeting parallel to the walls of the dike.

The fine-grained, altered feldspar that makes up 60 to 70 percent of the felsitic rock in one thin section is probably orthoclase in large part, as 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.

CARBONATE ROCKS

The rare earth minerals occur in deposits characterized by abundant carbonate minerals, barite, and quartz. These constituents have been deposited along mineralized shear zones, in veins an inch to about 20 feet thick, and in one remarkable carbonate body 2,400 feet long and as much as 600 feet wide.

Mineralogy

The carbonate rocks consist chiefly of calcite, dolomite, ankerite, siderite, quartz, barite-celestite, locally bastnaesite and parisite, and small quantities of many other minerals including crocidolite, chlorite, biotite, phlogopite, muscovite, sphene, allanite, monazite, magnetite, hematite, limonite, galena, pyrite, chalcopyrite, tetrahedrite, malachite, azurite, cerussite, aragonite, wulfenite, fluorite, apatite, thorite, and an unidentified rare earth calcium-magnesium carbonate mineral.

The predominant carbonate minerals in the deposits are calcite, dolomite, ankerite, and less commonly siderite. The carbonate minerals range from white to cream-colored or gray. The weathering of ankerite or siderite causes limonite staining in and near the veins, and the dark brown color of some weathered surfaces suggests the presence of manganese locally in the carbonate. In some thin sections, hematite or limonite occurs parallel to crystallographic directions in the carbonate mineral from which it was probably derived.

The carbonate minerals make up at least half of the material in most veins, but they range from 0 to 100 percent. Calcite predominates in most of the Sulphide Queen carbonate body, which is about 60 percent carbonate mineral, but one variety of rock found in the mass is dolomitic. 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, calcite and dolomite are commonly sheared, giving the rock a foliation, and crocidolite and bastnaesite are concentrated along the foliation planes. Late calcite replaces barite and occurs in veinlets cutting the other common minerals. 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.

Barite is a widespread vein mineral, in amounts that range from 0 to 65 percent chiefly, although some veins an inch or two thick are largely barite. Barite constitutes as much as 65 percent of the rock locally in the Sulphide Queen carbonate body, and averages 20 or 25 percent of this mass. The barite contains variable amounts of strontium, and some of it is nearer celestite than barite in composition. The barite in the veins and the large 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 common in thin section.

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. 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 shown on the map, barite surrounds quartz crystals and lines cavities as though deposited after the quartz. These examples indicate that barite was deposited at several stages in the paragenesis.

The rare earth minerals thus far recognized in the veins and carbonate rocks include bastnaesite, parisite, monazite, allanite, and an unidentified rare earth-bearing carbonate mineral. Of these the most abundant is bastnaesite, which constitutes 5 to 15 percent of much of the large 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. In color the bastnaesite is various shades of pale cream, yellow, greenish-yellow, reddish yellow, and reddish brown. Most of the grains are tabular. Rarely in high-grade veins the grains are 2 or 3 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. In addition to the tabular form, small hexagonal prisms of bastnaesite are found locally in the large carbonate body.

The properties of bastnaesite from other parts of the world are summarized by Glass and Smalley (1945). The mineral has been found at Bastnäs, Sweden; Ruanda-Urundi, Belgian Congo; Madagascar; Kychtym, Ural Mountains, Russia; Gallinas Mountains near Corona, New Mexico; Jamestown, Colorado; and at St. Peter's Dome near Pikes Peak, Colorado. The Mountain Pass bastnaesite at the Mocam shaft, as determined by Jewell Glass of the U. S. Geological Survey, is uniaxial positive, with indices of 1.722 and 1.823, and birefringence 0.101. Optical properties, chemical composition, and X-ray powder diffraction patterns are similar to these properties of other bastnaesite.

The bastnaesite grains in thin section generally have good crystal form and are very rarely altered or replaced by other minerals. They are set in a matrix of carbonate or various proportions of carbonate, quartz, barite, limonite, and other minerals. Some of the crystals in the thin veins are broken and the fractures filled by mixtures of carbonate, quartz, and barite, suggesting a relatively early age paragenetically. In the Sulphide Queen carbonate body, the small bastnaesite crystals are mostly interstitial to the coarser eyes 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.

Monazite is found as brown or reddish brown crystals in the large carbonate body, chiefly in the dolomitic parts, and it is presumed to be present in some of the rare earth-bearing radioactive shear zones in several parts of the district. Parisite has been definitely identified only in and near the Sulphide Queen carbonate body, where it occurs locally in small quantities in the carbonate rock and one granite sample. A rare earth mineral, as yet unidentified, composed of carbonate of calcium, magnesium, and cerium earths (Jaffe, 1952), has thus far been found only in an area about 150 feet in diameter in the Sulphide Queen carbonate body.

Quartz occurs in the veins in various proportions, generally from 5 to 40 percent but ranging from 0 to 100 percent. A few veins that are essentially all quartz are as much as 6 feet thick. They are found chiefly near granite intrusives 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 in the carbonate veins is generally fine-grained. It 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. In one thin section of rock near the south end of the large carbonate body, the quartz appears to have been deposited in three successive growth layers, in cavities formed by leaching of calcite, which is absent from this rock. In other sections, calcite surrounds quartz crystals. As in the case of the other common minerals, the paragenesis of quartz is not simple, and it was deposited at several stages which are generally late in the sequence.

Sulphide minerals that have been found in the district in small quantities include galena, pyrite, and copper-bearing sulphides such as chalcopyrite and tetrahedrite. Pyrite has been found in the veins and altered wall rocks underground in the ~~Mocam~~ Birthday and Sulphide Queen mines, and weathering of pyrite may account for some of the limonite staining found near the veins at the surface. Azurite and malachite that occur sparsely along fractures was perhaps derived through the weathering of copper-bearing sulphides. Small grains of galena are scattered through the veins and large carbonate body, and cerussite has been found in a pit in the northern part of this body. A few grains of wulfenite, lead molybdate, have been found on the dump of the Birthday shaft.

The carbonate rocks contain a variety but small quantity of silicate minerals, such as crocidolite, the fibrous blue soda-amphibole; phlogopite and biotite; muscovite; chlorite; allanite; sphene; and thorite. Phlogopite and biotite have formed around the edges of small fragments of feldspathic rock such as syenite or gneiss by reaction with the carbonate material, and also occur as scattered flakes locally in the large carbonate body. Crocidolite is associated with both the potash-rich igneous rocks and the carbonate rocks. Veinlets of crocidolite occur in the various igneous rocks, particularly the shonkinite. 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 sub-parallel orientation along shear planes which bend around the barite grains, imparting a foliation to the rock. The occurrence of fibrous soda-amphibole at Mountain Pass recalls its similar association with alkalic and carbonate rocks in other parts of the world. The absence of typical contact metamorphic minerals, such as diopside, idocrase, and garnet from the Mountain Pass carbonate rocks is significant.

Thorite occurs in small, dark red to reddish brown, shiny grains, mostly 1 mm or less in diameter, in a number of the veins and radioactive shear zones in the district. The thorite is mostly metamict, with variable indices around 1.70. Parts of some grains are clear and uniaxial positive.

Apatite and magnetite are relatively abundant in the igneous rocks and also occur locally in the large carbonate body in amounts that rarely exceed a small fraction of a percent. Hematite and limonite are common along the veins and shear zones, derived in large part through the weathering and alteration of iron-bearing minerals such as siderite and ankerite, biotite, pyrite, and magnetite. Fluorite is a minor constituent of some of the igneous rocks, the veins, and the large carbonate body. In the veins and carbonate body, it is present only locally, in amounts that rarely exceed a percent. The fluorite typically occurs as tiny grains less than 1 mm in diameter along seams, veinlets, and fractures, indicating its crystallization late in the paragenetic sequence.

Structural features of the carbonate rocks

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 north of U. S. highway 91 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 transect the foliation.

The mineralized shear zones are zones about 1 to 20 feet thick characterized by parallel shear planes, gouge, and brecciation. The rocks near the zones are altered, chloritized, limonite-stained, and laced with many veinlets or stringers of carbonate mineral, quartz, or barite. Many of these shear zones contain bastnaesite, monazite (?), or thorite locally. In addition to the numerous veinlets, perhaps 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. 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. The individual shear zones, as exposed in prospect pits, do not seem persistent along the strike, but rather are irregularly staggered or en echelon in a zone several hundred feet or more wide, such as the Windy group of prospects and the Ray-Willmore-Welch prospects about 3,000 feet south of the Highway Maintenance Station.

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 limonite along fractures, and the radioactivity present along some of the zones. The content of rare earths and thorium varies markedly at different points across the width of a mineralized shear zone. The sheared gneiss is illustrated by a thin section of rock from a prospect pit a mile south of the Windy prospects, at the southeastern corner of the mapped area. The granitic gneiss, composed chiefly of microcline, quartz, biotite, and minor zircon, is fractured and altered. Quartz, chlorite, calcite, iron oxides, and a little thorite occur as veinlets along the fractures, and chlorite, calcite, and iron oxides occur as alteration products of the minerals of the granitic gneiss.

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 are altered, and veinlets of carbonate, quartz, limonite, hematite, 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.

An alteration zone 100 to 200 feet wide extends westward several hundred feet from the southwest tip of the Sulphide Queen carbonate body, in line with a siliceous, bastnaesite-rich part of the body. The rock in this zone, which is probably altered granitic gneiss, is red because of disseminated hematite. In thin section, orthoclase makes up 75 percent of the rock, and hematite occurs as a reddish dust in the feldspar. Other constituents, which make up 1 to 5 percent of the rock, include allanite, quartz, opaque minerals, apatite, zircon, and 5 to 10 percent of secondary calcite and hematite. The calcite replaces the feldspar and occurs as irregular veinlets.

Breccia veins found at several places in the district contain scattered fragments of granite, syenite, shonkinite, or gneiss in a matrix of 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, for example, dark biotite syenite fragments are enclosed in pink 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, exposed over a length of 150 feet, dipping 70°S. in shonkinite. Fragments of shonkinite and syenite make up about 15 to 25 percent of the width of the vein.

Breccia fragments of various older rock types (see pl. 7A) 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. Some of the angular feldspathic wall-rock fragments of the breccia are but little rotated, but in other places well-rounded rock fragments of several rock types are assembled, 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 from the solutions. Another thin breccia vein occurs between the north end of the large 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.

A planar structure is evident in many of the carbonate deposits. Part of this is layering or banding that is apparently a primary feature of the veins, and part is a foliation that appears to be due to shearing. One type of layering, due to variation in grain size and concentration of opaque minerals in layers of carbonate-barite rock about an inch thick, is well exposed in the satellitic mass just east of the north end of the large carbonate body. Opaque minerals are concentrated in thin bands in several thin sections of carbonate rock.

Part of the planar structure appears to be a foliation due to shearing, and is generally parallel to the walls of a carbonate body. Barite grains, some of which are strung out along streaks in the rock, 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. Thin seams of later barite along shear planes also appear as a foliation in the large carbonate body.

The mineral content of the tabular vein-like 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 duplicated in any other veins examined.

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 plate 4. 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 map 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 and parallel to 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 stock. 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 before the circulation of mineralizing solutions had ceased.

The concentration of veins in the belt shown in plate 4 does not necessarily mean that rare earth deposits are absent from other parts of the district. The close relationship between the rare earth-thorium deposits and the potash-rich intrusive rocks suggests possible occurrences near other dikes outside the belt shown in plate 4, 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 body on Mineral Hill, but rare earth minerals are not known to occur in them.

A few veins composed chiefly of calcite and quartz occur in the area north of the transverse fault a few hundred feet north of the Birthday shaft, and 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.

Numerous pits have been dug in silicified and altered rock along the Clark Mountain fault. Veinlets of malachite, azurite, and limonite 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 prospected in the gneiss east of the fault, for example 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 zinc, lead, and silver, and stibnite is relative 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 at least part of the mineralization in the district, but not necessarily the rare earth mineralization. Fluorite is abundant in several deposits in Paleozoic dolomites north of Clark Mountain, but it is not known in deposits west of the Clark Mountain fault south of Clark Mountain.

Known rare earth-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 ~~Mosam~~ 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 most remarkable concentration of rare earths known in the district, because of its large size, although parts of some thin veins such as the original discovery vein near the Birthday shaft are equally rich or richer.

The old Sulphide Queen gold mine (see pl. 7B) consists of an inclined shaft, about 320 feet deep, and about 2,200 feet of drifts on 4 levels. 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 encountered in the mine is apparently due to thorium, which is in strongly sheared, chloritized rock, associated with the iron and manganese oxides. Several thin carbonate veins are also found in the workings, and these contain rare earths, probably as bastnaesite.

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 more than a dozen prospect pits have been dug. Some of these pits show no evidence of mineralization; others expose shear zones, some of which are presumably radioactive, along which the gneiss is chloritized and cut by many veinlets of calcite, quartz, hematite, and limonite. 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,

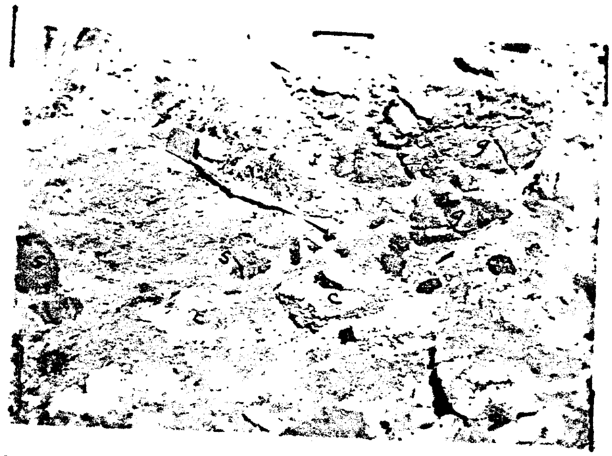

Plate 7A.—Breccia fragments in gray carbonate groundmass, Sulphide Queen carbonate body. g, gneiss; s, syenite, dark because of phlogopitic reaction rim; c, fragments of older carbonate rock.

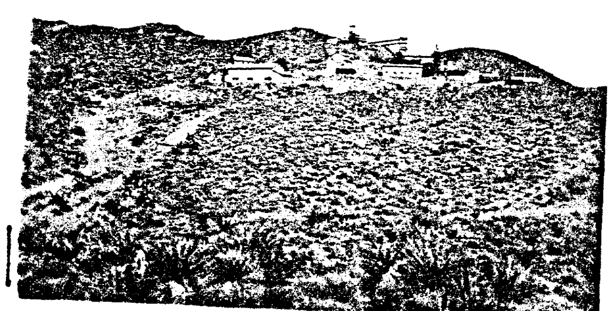

Plate 7B.—old Sulphide Queen gold mill.

but no rare earth or thorium minerals have been found in this area.

South of U. S. highway 91, no rare earth-bearing veins have yet been found in the area northeast of the fault that passes near the Highway Maintenance Station. Veins and mineralized shear zones occur in the area southwest of this fault and north of the transverse fault that extends southeastward from Grover Spring, especially in the belt outlined in plate 4. 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 essentially mineralized shear zones. As exposed in the prospect pits, many closely spaced, steeply dipping, subparallel fracture-surfaces are coated with limonite, hematite, 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 out of 7 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 barite grains oriented parallel to the walls.

Mineralized shear zones that are commonly radioactive occur in the vicinity of the two shonkinite-syenite stocks northeast of Grover Spring. Those encountered in the mapping are shown on the geologic map of the district as veins. The radioactivity appears to be due largely to thorium and is mostly in seams associated with iron oxides. Small grains of thorite have been found locally in these zones.

At the Rathburn prospects, 3,800 feet S. 20° E. of the highway Maintenance Station, several west- to northwest-trending silicified faults constitute a fault 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 sulphides, and iron oxides. Other nearby faults 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 may be of a different age from that of copper and gold. A few grains of pyrite, copper-bearing sulphide, and malachite have been found in several other prospect pits, for example several 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 gniess but of no known value. Several carbonate veins, about 2 feet thick on the average, occur in the gneiss around the granite mass on Mineral Hill, but rare earth minerals have not been found in them.

In the pre-Cambrian block south of the transverse fault that passes 1,500 feet north of the Windy prospects, veins occur in several areas, as shown in plates 1 and 4. 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, radioactive 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 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 about 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 limonite. Sparse grains of bastnaesite were found in 5 out of 8 thin sections from this vein. Just a few feet southeast of the pit the vein lies alongside and parallel to a dike of shonkinite or biotite-rich syenite one foot thick. The dike was sheared after its emplacement, forming numerous shear planes parallel to its strike 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.

In the Windy No. 1 pit and in other exposures to the southeast, purple fluorite occurs as a minor constituent. From the position of the pits and the distribution of radioactivity, the Windy group of prospects appears to be a zone of parallel or imbricate sets of mineralized fractures. Individual veins in this zone are as much as 4 feet thick but are discontinuous and traceable for only short distances, beyond which other mineralized fractures, perhaps 100 feet to one side of the projected strike of the vein, may be found over short intervals. The entire zone is at least 2,800 feet long, and the fractures that are locally mineralized are mostly in a width of 200 feet. The radioactivity is greatest in the relatively fresh exposures in pits, and may be hidden by the overburden in part of this zone.

At 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, limonite, calcite, and thorite(?).

Several veins in the general area 2,300 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.

STRUCTURAL FEATURES OF THE DISTRICT

Faults

The district is bounded on the west and north by large faults, and many other faults have been mapped in the district. Other faults are no doubt present but unmapped because of the obscurity of small displacements in the heterogeneous pre-Cambrian gneisses, and the difficulty of tracing faults that parallel the pre-Cambrian foliation and layering. 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 structure are traced by the abrupt change, at the fault, 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 expression.

With few exceptions, all the mapped faults strike in the northwest quadrant and dip southwestward. Three faults mapped near Wheaton Springs 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 largely 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 degrees and probably averages about 55 degrees (see cross-sections, pl. 8). 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 limonite-stained. They contain scattered sulphide minerals and have been prospected by small pits, but rare earth minerals have not been found along the fault. Chlorite, epidote and some calcite are conspicuous in parts of the gneiss as much as 1000 feet from the fault, in a zone in which shear planes, generally parallel to the fault and in places at an angle to the gneissic foliation, are abundant. The chloritic alteration is mostly in the mafic and garnet-biotite gneisses, and some andesite dikes are similarly altered.

A prominent transverse fault offsets the trace of the Clark Mountain fault at least 1200 feet, in the area about 2400 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 fault over part of its extent. The fault dips 65°-70° S. That the displacement is considerable, is indicated by the abrupt truncation of the shonkinite-syenite body and associated dikes and veins near the Birthday shaft, inasmuch as the potash-rich dike rocks have not been found north of the fault. One andesite dike also terminates at the faults, suggesting post-andesite movement. Brecciation 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 mineralization. West of this point, in the area north of the Birthday shaft, the faulting appears to be mainly in two zones as much as 600 feet apart, between which is a wedge of pre-Cambrian gneiss.

The biotite granite gneiss and the adjoining mixed gneisses (units D and E on pre-Cambrian map, ~~fig.~~ pl. 3) occupy a wider area north of the fault than south of it, and the trace of the westward-dipping Clark Mountain fault is displaced relatively eastward north of the transverse fault. These relationships are best explained by considering the block south of the fault as upthrown, therefore a reverse fault. The horizontal component of movement is unknown, but the relative positions of units on the two sides suggest an eastward as well as upward movement of the block south of the fault. This supposition is based largely on the distribution of poorly-defined pre-Cambrian mixed rocks, but if correct, the continuation of the potash-rich rocks north of the transverse fault might lie in the gravel-covered area near the Clark Mountain fault, perhaps at some depth below the present surface, or even west of the Clark Mountain fault.

Another fault that is well-marked by topographic depressions and saddles extends southeastward from a point on the Clark Mountain fault, southeast of Grover Spring, passing about 1,500 feet north of the Windy prospects. This fault is evident from the differences in pre-Cambrian rocks on the two sides and the truncation of shonkinite and granite dikes.

A fault apparently of considerable displacement has been traced from the vicinity of the Highway Maintenance Station southeastward more than two 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 appears to have moved southeastward and downward relative to the northeast side. The actual displacement is not known, but the horizontal component of movement is perhaps 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 is thought to represent the lower part of this faulted composite intrusive, that solidified slightly later than the shonkinite-syenite portion. 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 supposed fault movement is also indicated by the relative positions of pre-Cambrian units and andesite dikes on both sides of the fault. The andesite dike swarm that cuts through the shonkinite-syenite stock northeast of Grover Spring extends eastward to the fault, then is displaced nearly a mile to the northwest, whence it continues eastward south of Wheaton Wash.

The fault is poorly exposed northwest of the Highway Maintenance Station, but very likely it passes not far southwest of the large carbonate body near the Sulphide Queen mine, 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. Inasmuch as 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 alluviated area west of Mexican Well is a possible site for prospecting.

The east-trending silicified fault north of Wheaton Wash, and the fault zone that extends both east and west of the two parallel east-trending granite dikes 3,300 feet N. 30° E. of Grover Spring, were probably at one time along the same trend that later was offset by the fault that passes near the Highway Maintenance Station. The two parallel granite dikes in this zone cut the shonkinite-syenite body but were emplaced in fractures parallel to the fault zone, suggesting the fault is post-syenite and pre-granite, hence pre-mineralization.

Some of the faults in the district are marked by such features as drag folds, brecciation, gouge, and slckensides. 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 body 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 a 2-foot thickness of quartz 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 reddish, yellowish, or purplish brown.

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 alteration in the volcanic rocks. Garden Spring is in a large 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. Faulting was not noted at the spring about 4,000 feet S. 10° E. of the Highway Maintenance Station but this spring is aligned with a number of small faults, constituting a fault zone, extending S. 60° E. from the spring.

Several small tufa deposits in the district probably indicate former springs, and some of these are near faults, for example 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 intrusive of Mineral Hill where the fault crosses the wash. Other tufa deposits that are within a couple of hundred feet of known faults are found near the bend in the wash one 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 nearby rocks.

Age of the faulting

The faults in the district are of several ages. Zones of probable pre-Cambrian movement are indicated by drag folding and 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 intrusives were probably controlled in part by a northwest-trending structure in addition to the foliation. 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, rare earths, or thorium that are genetically related to the intrusive rocks. Some shear zones are thus dated as post-shonkinite and pre-mineralization. The composite intrusive body 3,300 feet N. 30° E. of Grover Springs is cut by two parallel east-trending granite dikes a few feet apart, suggesting post-shonkinite, pre-granite faulting along the fault zone both east and west of these granite dikes. At one point about 1,500 feet east of the two parallel granite dikes, an andesitic (?) dike that appears to follow the fault is sheared, as though involved in later faulting, suggesting both pre- and post-andesite movement on this fault zone.

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 transect the potash-rich intrusive bodies and the rare earth mineral deposits, dating the fracturing as post-mineralization and pre-andesite.

Finally, many of the faults are post-andesite, as the andesite and felsite dikes are displaced by the faults. For example, the felsite dike about 800 feet south of Mexican Well is cut by a fault that trends N. 20° E. The andesite dike swarm trending eastward from the shonkinite-syenite body 3,000 feet N. 70° E. of Grover Spring is apparently displaced about a mile by the fault that extends southeastward from the Highway Maintenance Station.

The fact that many andesite dikes approach or intersect the Clark Mountain fault from the east, but none have been observed to cross the fault, suggests that there has been considerable post-andesite movement on the Clark Mountain fault. Near the Clark Mountain fault the rocks are altered and silicified, and andesite as well as older gneiss and shonkinite are altered, producing such minerals as chlorite, calcite, and epidote. The Clark Mountain fault cuts the Mescal thrust, along which Paleozoic sediments are thrust over Cretaceous (?) volcanic rocks, hence both these faults are younger than the volcanic rocks. According to Hewett (1951) 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-mid-Cretaceous, possibly early Tertiary or late Cretaceous.

ORIGIN

The Mountain Pass district typifies the association, recorded in many areas, of alkalic rocks, carbonate rocks, abundance of volatile constituents and extraordinary concentrations of certain uncommon elements, in a metamorphic complex that is dominantly migmatite and granitic gneisses. The ultimate origin of the rocks and associations remains a fundamental problem.

Various hypotheses have been set forth to explain the association of alkaline igneous rocks and carbonate rocks. Among them are, for example, the metamorphism of pre-Cambrian saline deposits (Jensen, 1908), magmatic differentiation (Bowen, 1928), magmatic differentiation with volatile substances such as CO_2 and F as important factors (Smyth, 1913), assimilation of limestone (Daly, 1918), and the action of highly energized alkali-rich emanations on sialic rocks (Holmes and Harwood, 1936, p. 249).

Summary of evidence

Any hypothesis accounting for the origin of the carbonate rocks, the concentration of uncommon elements, and the association with alkalic dike rocks in the Mountain Pass area should take into consideration the following features:

1. The veins and carbonate rocks are spatially and genetically related to the potash-rich igneous rocks. The largest body of carbonate rock and the greatest concentration of carbonate veins lie near the southwest contact of the largest shonkinite-syenite stock in the district.

2. The carbonate veins not only transect the pre-Cambrian foliation but they also cut across and therefore postdate all the potash-rich dike rocks, and appear to be in fractures in the large shonkinite-syenite body. At no place do the gneisses and the potash-rich intrusive rocks cut across any of the carbonate rocks.

3. Shearing occurred after the emplacement of much of the carbonate rock, but before the rare earth mineralization had ceased, which is shown by the shear foliation in the large carbonate body and the truncation of carbonate veins by mineralized fractures.

4. The known rare earth-thorium deposits are in a belt 6 miles long (see pl. 4), in which discontinuous shear zones cutting syenitic dike rocks and carbonate rock are locally mineralized, indicating that fault movements were associated with the igneous activity and with the mineralization.

5. The carbonate material appears to have been intruded into its present position. The 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.

6. The veins and the large carbonate body contain exceptional concentrations of rare earths and other uncommon elements.

7. Limestone of sedimentary origin is not known in the pre-Cambrian rocks of the district, which are largely granite gneiss and migmatite.

8. Typical contact metamorphic silicate minerals, such as diopside, tremolite, idocrase, and garnet, are absent from the carbonate rocks, but phlogopite or biotite formed locally by reaction between carbonate material and included fragments of feldspathic rocks such as syenite and gneiss. Crocidolite occurs as a late mineral chiefly along shear planes in the carbonate rock.

Possible modes of origin

Carbonate rocks, alkalic igneous rocks, and relatively large concentrations of certain uncommon elements, are associated in many districts of the world. In many areas the limestone syntexis hypothesis of Daly has been called upon 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 occurs within many miles of the complex of alkalic and carbonate rocks, and for these areas some geologists have called upon a magmatic source for the carbonate as well as alkalic rock constituents. Although the data of physical chemistry indicate that a dry carbonate melt is unlikely to occur under conditions prevailing in the earth's crust, carbonate rock might develop from a magmatic differentiate with large concentrations of water, fluorine, CO_2, and other volatile substances.

Some of the carbonate rock possibly could have originated from a sedimentary limestone lens in the granitic and other gneisses, which under intense metamorphism became redistributed, by plastic deformation and circulating solutions, into the discordant bodies now found. The exceptional quantities and wide dissemination of the rare earths and barium in the carbonate rock are awkward to explain in this way, however, inasmuch as comparable quantities are not found in any known sedimentary rocks or present-day sediments. Although barite is not uncommon in sedimentary limestones, a content of 20 to 25 percent would be exceptional. The evidence given in items 2, 7, and 8 in the above summary suggest that the carbonate material was not of sedimentary origin although it does not disprove it, for the rare elements might have been introduced into a sedimentary limestone from a magmatic source, or the dike- or veinlike bodies along fractures in the shonkinite-syenite and the gneiss might have been deposited from hydrothermal solutions that derived some of their constituents in passing through the large carbonate body.

The possibility might be considered that a magma, perhaps of granitic composition, invaded the overlying Paleozoic limestones and dolomites, and the reaction and assimilation produced a magma from which the potash-rich dike rocks and the carbonate rocks developed several thousand feet below the sedimentary rocks. According to the cross-sections (pl. 8), the basal Cambrian rocks appear to have been at least 3,000 feet above the present erosion surface in the Sulphide Queen area. That a magma might have reached the surface, and hence the Paleozoic limestones, is suggested by the possible correlation, wholly unproved, between the intrusives and the Cretaceous (?) volcanic rocks south of Grover Spring. A relation of the Paleozoic sediments to the petrogenesis is therefore considered possible but there is no evidence to support it.

The most plausible hypothesis of origin is that the carbonate rocks and veins are the final products of the differentiation of the alkaline magma that produced the potash-rich series of igneous rocks. The sequence of emplacement of the igneous rocks, consistent throughout the district, is well established from the earliest shonkinite through progressively more leucocratic syenites to granites with increasing silica content, and all these are cut by a few fine-grained lamprophyric shonkinite dikes. The development of this sequence by magmatic differentiation might lead progressively to a late differentiate rich in carbon dioxide and the rare constituents. Evidence supporting a magmatic source for the carbonate material includes items 1, 2, 5, and 6 in the summary of evidence given above, and a magmatic source is not out of harmony with the other evidence listed.

Although a magmatic source for the carbonate material appears reasonable from the available evidence, certain theoretical problems are unanswered. It is difficult to explain the origin of magma of such 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 bariet is also not completely known. The evidence indicates that at least some of the vein-like carbonate bodies formed by deposition from hydrothermal solutions. The large Sulphide Queen carbonate mass, however, may have been formed, in part at least, from a relatively thick magmatic solution, highly charged with volatile substances such as CO_2, F, and SO_3, or it may have formed entirely from less concentrated hydrothermal solutions.

Comparison with other areas

The association of carbonate and alkalic igneous rocks, and its implications, have been discussed by many writers (for example Smyth, 1913; Shand, 1947, pp. 304, 312-329; Daly, 1933, pp. 505-512, 564-565; Turner and Verhoogen, 1951, pp. 341-342). The ultimate origin of the rocks and the association remains a fundamental problem. 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 the following pages, the geologic features of many other comparable areas are summarized. 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. In many of the areas described, feldspathoidal rocks occur; at Mountain Pass, however, the rocks are alkalic and remarkably rich in potash, but feldspathoids have not been found in them.

Haliburton-Bancroft area, Ontario: There is abundant evidence that feldspathoidal rocks may form through the reaction of magma upon carbonate rocks, and the limestone syntexis hypothesis has found wide acceptance to explain the association of carbonate and alkalic rocks in many areas. Perhaps the best-known illustration of this relationship is the Haliburton-Bancroft area, Ontario, described in the classic paper of Adams and Barlow (1910), upon which the concept of limestone syntexis appears to have been based, in part at least, by later writer. The occurrence in this area of nepheline syenites at the borders of granite masses where they cut limestone, and the gradation from limestone to nepheline syenite containing calcite grains, indicate the origin of the nepheline syenite by limestone syntexis.

In the same region near Bancroft, Ontario, it has also been shown (for example Chayes, 1942) that sedimentary limestones may, because of their mobility under stress, be forced to intrude other rocks by deforming plastically. Marble bands included in granite, for example, were mashed, and they intruded other rocks without actually becoming fluid. The term carbonatite is used by Chayes for intrusive carbonate rocks regardless of whether sedimentary or igneous in origin. The carbonatites contain inclusions of all the rocks of the region except younger nepheline syenites, and have a foliation which bends around the inclusions. Minerals such as phlogopite, diopside, apatite, tremolite, forsterite, and garnet are present in the carbonatite.

Ice River complex, British Columbia: In the Ice River complex of alkaline rocks, British Columbia (Allan, 1914, pp. 173-175), calcite is a common accessory constituent and is invariably present as a primary constituent in those types that occur at or near the contact with the abundant crystalline limestone of the area. The calcite appears to be distinctly foreign to the magma and derived from the neighboring limestone.

The Haliburton-Bancroft and Ice River districts are samples of those areas in which the presence of sedimentary limestone is interpreted as a factor in the development of the feldspathoidal rocks. In many other areas, described on the following pages, alkalic rocks, with or without associated small carbonate bodies, occur with no evident sedimentary limestone to invoke as a contributing factor to the relationship. Many of these, like Mountain Pass, are areas of gneiss chiefly of granitic composition without sedimentary limestones.

Iron Hill complex, Colorado: The Iron Hill complex (Larsen, 1942) of Colorado underlies about 12 square miles. According to Larsen, the oldest rock in the stock is a mass of dolomitic marble over a mile across. Smaller bodies of similar marble occur as small inclusions in the igneous rocks of the stock and as hydrothermal deposits in the surrounding pre-Cambrian granite, gneiss, and amphibolite. The main mass of marble is believed to have formed as a large hydrothermal deposit in the throat of a volcano, though it may have been intruded as a carbonate magma or it may be an inclusion of pre-Cambrian marble.

Igneous rocks of the Iron Hill stock include the melilite rock "uncompahgrite"; pyroxenite, which makes up 70 percent of the area; ijolite; soda syenite; nepheline gabbro and quartz gabbro. The most widespread hydrothermal products are aegirine and a soda amphibole with or without phlogopite and other minerals, which occur in the hydrothermal carbonate rocks cutting the pre-Cambrian gneiss and which were also introduced into the dolomite during its hydrothermal metamorphism by the pyroxenite. Numerous veins of granular dolomite, containing some quartz, alkalic feldspar, galena, sphalerite, pyrite, fluorite, and some silicates, cut the rocks of the stock. Veins of dolomite and calcite, apatite, quartz, alkalic feldspar, and martite cut the marble.

The marble is mostly dolomitic but part is calcitic. It contains a few percent apatite, limonite stains, and widespread and locally abundant pyrite. Near the contacts with the intrusive rocks the marble contains streaks and bunches of generally fibrous aegirite and a soda-amphibole ranging from soda tremolite to glaucophane, phlogopite, apatite, and local microcline, albite, quartz, anatase, and fluorite. Phlogopite occurs in small amounts in streaks in all parts of the marble and is commonly associated with veins of iron ore. The marble is not bedded. Where the pre-Cambrian granite about the Iron Hill stock has been impregnated with and replaced by aegirite and sodic amphibole, a rock identical with the "fenitized granite" of Brögger has been produced Larsen, 1942, p. 34).

<u>Libby, Montana</u>: At Libby, Montana (Larsen and Pardee, 1929), carbonate veins are associated with a stock of alkalic rocks 2½ by 3½ miles in area, which occurs in slate, quartzite, and limestone of the pre-Cambrian Belt series. The stock is composed of pyroxenite, nepheline syenite, syenite, and a few small dikes of granite, in order of decreasing age. The pyroxenite is altered locally to fibrous amphibole, and parts of it are nearly all vermiculite

Aegirine and sphene were introduced hydrothermally to the syenite. The thicker veins that cut the pyroxenite are mostly quartz, and the central parts of most veins are quartz. Near the walls the veins contain vanadiferous aegirine, microcline, strontianite, celestite, pyrite, and chalcopyrite, with a little fluorite, galena, and sphalerite. Within a few inches of the veins, the pyroxene of the pyroxenite is completely altered to a fibrous amphibole, related to actinolite and glaucophane, and locally a little calcite, quartz, and sulphides are introduced into the altered pyroxenite.

Magnet Cove, Arkansas: The Magnet Cove area has been described by many writers, among them Williams (1890), Washington (1900), Landes (1931), and Ross (1941, pp. 23-26). Magnet Cove is a basin-like area 2 miles in diameter surrounded by a nearly continuous rim of Cretaceous igneous rocks. The igneous rocks include a wide variety of types characterized by nepheline and, in one of the abundant types, by pseudoleucite. Paleozoic sandstone, novaculite, and shale metamorphosed to slate, surround the igneous complex and are altered near it. In the Cove are sparse exposures of altered slate, novaculite, igneous rocks, volcanic agglomerate, tufa, and a coarse-grained calcite rock. The area is noted for its great variety of minerals. Among the minerals of the calcite rock are monticellite, magnetite, apatite, dysanalite (perovskite), wollastonite, pyrite, vesuvianite, rutile, brookite, anatase, phlogopite, and thomsonite. The origin of the calcite rock is uncertain. It was considered by Landes to be a xenolith of sedimentary limestone brought up by the magma from depth.

Alnö Island, Sweden: The alkaline and carbonate rocks of Alnö Island, Sweden, have been studied in detail by von Eckermann (1948). Here, in an area about 3 miles in diameter, alkaline igneous rocks and a variety of carbonate rocks are associated. The pre-Cambrian migmatite, which surrounds the Alnö complex, was altered near the intrusive center to produce a rock of generally quartz syenitic, syenitic, or nepheline syenitic composition called fenite, which was formed in situ by replacement of migmatite. The degree of alteration increases inward toward the center of the complex, forming successive shells of different rock types. The migmatite grades inward through a zone of fractured and iron-stained migmatite, in which the quartz is strained and granulated, to the fenite, which formed in situ and retains the east-west structure of the migmatite. The fenite is enriched in aegirine-augite and potash feldspar at the expense of biotite and quartz, and is richer in potash, iron, titanium, phosphorus, fluorine, and barium, and poorer in silica than the migmatite. The outer fenite zone is characterized by decreasing quartz percentage; next inward is a zone with no quartz, then a zone of nepheline-bearing fenite, and further inward a completely alkalized fenite. Toward the center from the fenite zones, the relict foliation of the migmatite is lost, through liquefaction of the material, and the structure of the inner zone is concentric.

A wide variety of both light- and dark-colored igneous rocks, many of syenitic and nepheline syenitic families, have been mapped and described by von Eckermann. They are believed to have originated partly as mobilized fenite and partly as igneous intrusives such as radial dikes and cone sheets.

The Alnö carbonate rocks have been classified by von Eckermann into (1) sövite, which includes almost pure calkite rocks, containing 90 percent or more calcite, where the calcite is not of sedimentary or biogenic origin; (2) rauhaugite, a dolomitic sövite; (3) alvikite, similar in sövite in composition but of deeper-seated origin; and (4) beforsite, which is like rauhaugite in composition, having dolomitic or dolomitic-sideritic carbonate, but of deeper-seated origin corresponding to alvikite. These rocks are further classified by appellative minerals such as biotite, apatite, or pyroxene when present in amounts of 4 to 20 percent. Other minerals present locally in the carbonate rocks are quartz, pyrite, albite, orthoclase, fluorite, magnetite, ilmenite, melilite, olivine, sphene, perovskite, garnet, natrolite, chlorite, antigorite, barite, knopite (cerium-perovskite), pyrochlore, and zircon. The biotites are both green and brown, and some have abnormal absorption schemes, apparently similar in these variations to biotites in the Mountain Pass carbonate rocks. The sövite also contains numerous fragments, believed to have dropped into the carbonatitic liquid from the fenite roof and converted to more pyroxenitic rocks through enrichment in iron chiefly. The fluidal banding of the carbonate rock bends around these inclusions.

The carbonate rocks ar Alnö in part have the form of cone-sheets. Von Eckermann calculated the foci of the alvikitic cone-sheets at a depth of about 2 km and the beforsite cone-sheets at 7 to 8 km. The carbonate dikes have generally distinct well-defined contacts and well-developed flow structure. Two barite veins are described, 1 to 3 meters wide, which contain near their centers 96 to 99 percent barite, and near their walls 40 percent barite, 40 percent calcite, and 20 percent fluorite.

The evidence concerning origin of the Alnö carbonate and alkaline rocks is discussed in detail by von Eckermann (1948, pp. 148-161), and pressure-temperature conditions existing during the formation of the Alnö rocks are inferred. The ultimate source of the carbonatitic liquid is problematical, but is believed by von Eckermann to be more nearly related to Smyth's "gas-hypothesis" than to Daly's "limestone-syntexis". There is no evidence of pre-Cambrian limestone bodies, to invoke as a basis for origin by limestone syntexis, within hundreds of miles of Alnö.

Fen, Norway: The Fen district of Norway was described in Brögger's classic monograph (Brögger, 1920) and later papers (Bowen, 1924, 1926; Brauns, 1936; Tomkeieff, 1938). The Fen complex occupies an area less than 2 miles in diameter in an extensive terrane of pre-Cambrian granite. Carbonate rocks are closely associated with alkaline igneous rocks which contain variable amounts of calcite. The carbonate rocks, which make up at least half of the area of the complex, occur chiefly in large masses but also in smaller vein-like bodies and mixed carbonate-silicate rocks. The 3 types of carbonate rock distinguished by Brögger are sövite, which is a magmatic carbonate rock consisting essentially of calcite, with apatite, biotite, manganophyllite, and microlite; rauhaugite, in which magnesium- and iron-bearing carbonates predominate, with apatite, barite, as much as 8 percent, and magnetite; and mixed silicate-carbonate rocks. Typical contact silicate minerals are absent from the carbonate rock. Within the carbonate mass are patches of iron ore and "Rodberg", which consist mainly of mixed hematite, magnetite, and carbonates.

Many of the alkalic rocks at Fen contain nepheline, and a variety of rock types are described and named by Brögger. Melanocratic rocks predominate. Near the borders of the complex, fenite was formed by intense contact metasomatism of the pre-Cambrian granite by melteigite-ijolite magma. The quartz of the granite is replaced by albite, biotite by aegirine, oligoclase converted to albite, and orthoclase to microperthite and albite. The most advanced product of this fenitization is an alkali feldspar-aegirine rock, fenite, or the darker, pyroxene-rich, tveitasite. Locally the fenite appears to have been mobilized, forming independent dikes. The carbonate rock was emplaced after the fenitization and the melteigite-ijolite series. Brögger concluded that the carbonate material was derived from the melting of an older limestone below the pre-Cambrian granite, although no such limestone crops out near Fen. Bowen (1924) concluded that the mixed carbonate-silicate rocks were formed by partial replacement of silicates by carbonates and that the pure carbonate rock represents complete replacement. Brauns (1936) advocated an igneous origin of the carbonate rock.

<u>Spitzkop complex, Sekukuniland, Eastern Transvaal:</u> The alkalic rocks at Spitzkop, Sekukuniland, have been described by Shand (1921) and by Strauss and Truter (1950). The Spitzkop complex, 3 miles in diameter, consists of carbonate rocks and alkalic rocks such as foyaite, ijolite, urtite, umptekite, quartz syenite, and alkali granite. Strauss and Truter have interpreted the gradation from the pre-Cambrian red Bushveld granite inward to alkali granite, quartz syenite, and red and white umptekite, as a process of fenitization. The change is shown progressively inward by a gradual change in feldspar color from red to white, decrease and disappearance of quartz, which is replaced by dark blue soda-amphibole in bunches of minute fibers, increase in size

and abundance of mafic constituents, and small but notable increase in grain size of the feldspar. These rocks have a concentric sheeted structure with centripetal dip.

The carbonate rock at Spitzkop occupies a circular area 4,000 feet in diameter in the alkalic complex near one edge. This carbonate rock was interpreted by Shand (1921) as a xenolith of Transvaal dolomite brought up about 14,000 feet. Later Strauss and Truter (1950a) considered it to be a product of magmatic differentiation, forming the top of a composite ring dike younger than the adjoining foyaite ring dikes. Four distinct varieties of carbonate rock are recognized by Strauss and Truter: (a) a narrow, complete outer zone composed of medium- to coarse-grained, banded, gray calcite rock, with local clots of apatite and magnetite; (b) fine-grained, brown-weathering, thinly laminated, dolomitic carbonate rock forms the main central mass and contains, especially near the periphery, as much as 4 percent apatite and euhedral magnetite with pyrite and limonite pseudomorphs; (c) yellow-weathering limestone, containing pyrite, limonite, serpentinous material, and fibrous deep blue amphibole, probably riebeckite, occurs in thin irregular veinlets cutting a and b; (d) black-weathering impure limestone in dikes up to 2 feet wide cuts both the coarse- and fine-grained varieties. The outer zone (a) has a concentric structure, and the banding is vertical or dips steeply outward. The inner mass (b) is dome-shaped, for the banding is concentric and dips outward at angles that increase toward the outer margin where it is vertical in places.

Shand (1921) pointed out that the limestone is recrystallized and contains magnetite, apatite, and the fibrous blue soda-amphibole, crocidolite. The crocidolite occurs as tufts enclosed in calcite and as larger masses, filling interstices between the calcite crystals, that seem to have been introduced during recrystallization of the limestone.

Other areas in Eastern Transvaal: Southwest of Spitzkop, a calcareous diatreme 200 feet long in granite is filled with agglomerate, with a red calcareous matrix, and is cut by limestone dikes.

At Magnet Heights, Sekukuniland (Strauss and Truter, 1950b), 5 diatremes in a row, the largest 150 feet long, are filled with agglomerate and are cut along their axes by a vertical vein of carbonate rock more than 1100 yards long and less than 12 inches thick. The carbonate rock is mainly fine-grained and massive, but is locally banded, and it contains chert, opaque minerals, phlogopite, and sulphides. The carbonate rock in the fissure is said to be a magmatic product.

A small body of limestone associated with shonkinitic pyroxenite at Palabora (Lulu Kop) in Eastern Transvaal is interpreted by Shand (1931) and DuToit (1931) as an older limestone rather than a magmatic product.

Chilwa series, southern Nyasaland: The Chilwa series of alkalic and associated carbonate rocks in southern Nyasaland has been described by Dixey, Smith, and Bisset (1937). The alkalic rocks occur in and near vents filled with brecciated feldspar rock containing as much as 13 percent K_2O. All the vents are expressed topographically by ridges and depressions. Nine large vents are greater than 0.25 mile in diameter. At least 5 of these contain bodies of crystalline calcite, and to a lesser extent iron and manganese carbonates, and at least two of the others have carbonates in the matrix of the agglomerates. Carbonates are also present in at least 4 of the 7 smaller vents described.

The syenitic rocks of the Chilwa series include such types as trachyte, solvsbergite, porphyritic biotite-bearing microsyenite and orthoclase-hornblende syenite. Nepheline-bearing rocks, which are generally later than the carbonate rock, include such types as foyaite, tinguaite, aegirine microfoyaite, nepheline syenite, ijolite, nephelinite, and phonolite. The pre-Cambrian granitic gneisses and younger sediments around the vents are commonly jointed, locally shattered, and red-stained, with fine irregular veins and films of iron oxide. Feldspathic material has been introduced into joints and foliation planes, and a green pyroxene locally replaces certain other minerals. The most advanced stage of alteration yields a feldspar-pyroxene (aegirine and aegirine-augite) rock comparable to the fenite of Scandinavian areas.

The larger vents of the Chilwa series appear to be vertical pipe-like intrusions, nearly circular in plan, 1 to 4 miles in diameter. The carbonate bodies in five of the vents range from 0.25 to 3 miles in diameter. At Muamb the gray crystalline limestone that forms the main part and center of the ven contains many clots and bands of feldspathic intrusive, which locally form mo of the rock. At Chilwa, gray crystalline limestone 1.5 miles in diameter for the main part of the vent and grades outward into a zone of feldspar rock about 3[illegible] feet wide. At Tundulu, a discontinuous ring of limestone, feldspar rock, and agglomerate occurs around a core of nepheline syenite. At Songwe, a circular area of agglomerate, with interstitial limestone in patches commonly a few inches to a foot long, surrounds a nepheline syenite intrusive a mile wide. Here and at Kangankunde, agglomerate and breccia of feldspar ro and gneiss contain many irregular masses of carbonate, generally less than

2 feet long but also larger. At Mkalonje and Nsengwa, the vents are filled mostly with feldspathic intrusive and related breccias, but carbonates are abundant in the matrix of the agglomerate and breccia.

Calcite is the chief carbonate in the Chilwa series, but iron and manganese carbonates are also present. These carbonate minerals in places are segregated into irregular masses or parallel streaks; in other places, one carbonate forms numerous small clots in another, or one type shows intrusive relations to another. All the large carbonate bodies have a vertical or near-vertical banding due to parallel arrangement of the carbonate or feldspathic streaks in bands an inch or two wide or larger. In places, angular fragments of feldspar rock are closely set in limestone which has a flow structure marked by streaks and patches of feldspar rock. In addition to the carbonate minerals, the Chilwa limestones contain apatite, magnetite, fluorite, biotite, strontianite, and veins of late quartz and chalcedonic silica. Aegirine, aegirine-augite, and tufts of pale blue amphibole occur in syenites, fenite, or granite.

Dixey, Smith, and Bisset concluded that the vents formed at least in part by explosive action, and this may be closely connected with the occurrence of the carbonates. The present exposures must be at least 7,000 feet below the original surface. The extensive alteration around the vents is ascribed to emanations accompanying the carbonate and orthoclase rocks, rather than to the nepheline syenite which is slightly younger than the altered rock (fenite) and the carbonate rock. The scarcity of limestone in the basement rock indicates that sedimentary rocks are unlikely to have yielded the limestone, and the authors conclude that the origin of the limestone is connected with the magma responsible for the vents and for the orthoclase rocks.

Shawa and Dorowa, Southern Rhodesia: The carbonate rocks in the ring structures at Shawa and Dorowa, Southern Rhodesia, are associated with alkalic complexes consisting of rocks such as ijolite, syenite, shonkinite, nordmarkite, granite, jacupirangite, pyroxenite, and serpentine, according to Mennell (1946, pp. 137-140). At Shawa, carbonate rock forms the core of a ring of syenitic and granitic rocks, 4 miles in diameter, in gneissic granite. The carbonate rock is about 2 miles in diameter, nearly circular in plan, and is separated from the syenite by a ring of serpentine. The carbonate rock consists chiefly of dolomite and other carbonates, but contains apatite and in places appreciable magnetite. The carbonate rock has distinct cleavage or banding with northwesterly strike.

At Dorowa, a complex about 1 by 2 miles in plan, in gneissic granite, has a core of carbonate rock about 500 yards in diameter, surrounded by a ring of syenite and granite, with which is associated some pyroxenite and shonkinite. Most of the carbonate rock is fine-grained and dolomitic, and it is locally ferruginous. At one described locality, coarse-grained carbonate rock has a north-trending foliation and contains magnetite, an asbestiform iron-bearing amphibole, and small flakes of mica. Some of the magnetite rock associated with the carbonate rock is said to occur in masses 40 or less feet wide and as much as 900 feet long, and to contain as much as 69 percent iron. Apatite is present in the magnetite rock, and there is a gradation to apatite-rich rock with minor magnetite.

Homa Bay area, Kenya: Pulfrey (1344) considered the limestone of the Homa Bay area to be carbonatite. The carbonate rocks here are associated with alkalic dike rocks such as ijolite, urtite, melteigite, nephelinite, phonolite, and shonkinite. The carbonatites have a crude ringlike or pluglike form. Some are almost pure carbonate, whereas others contain silicates such as melanite, phlogopite, vesuvianite, aegirine, aegirine-augite, apatite, and magnetite. Later ferriferous carbonatites cut the ea earlier carbonate rocks. The silicates show marked streaming in planes that are generally vertical but are locally inclined or contorted.

Eastern Province, Uganda: Four volcanic centers with carbonate cores occur in the Eastern Province, Uganda (Davies, 1947). Broadly speaking, each of the four is made up of 5 roughly concentric belts which, from the granitic wall rocks inward, are (a) granites with sodic hornblende; (b) kalisyenites, pulaskites, fenites, and their melanocratic counterparts; (c) mixed rocks in which are ijolite, nepheline syenite, melteigite, urtite, pyroxenite, biotite pyroxenite, and rocks showing every mixture of biotite, kataphorite, and diopside; (d) a magnetite-apatite-phlogopite band with insignificant amounts of silicates; (e) carbonatite, which is mainly a fairly pure limestone with widespread magnetite, apatite, phlogopite, pyroxene, hematite, and fluorite. At the outer edge of the limestone, minerals such as garnet, wollastonite, tremolite, koppite, and anatase occur. Locally, rocks comparable with the sövite and ringite at Fen, described by Brögger, are found. The magnesium content of the limestones is low. Siderite is noted only occasionally, but iron staining is common. Commonly, near their contacts, these rock types are intimately mixed, as on Tororo Hill, where rocks of the fenite type are mixed with limestones.

The largest carbonatite of the Eastern Provinces, Uganda, occurrences is that of the Sukulu complex, where carbonate rock $2\frac{1}{2}$ miles in diameter is separated from the granite wall rocks by a zone, 400 yards or less in width, containing a variety of the silicate rocks. The Bukusu complex is 4 to 5 miles in diameter, and carbonatite occurs in 3 areas, the largest about 1/2 by 1-1/2 miles in plan, in the interior of the complex. A few small dikes of carbonatite also cut the outer rock formation. The carbonatite at Tororo is pear-shaped in outline and about $1\frac{1}{2}$ miles long. The zone of rocks between the carbonatite and the granitic wall rock is rarely more than 400 yards wide, and it includes syenite, rare nepheline rocks, and a pipelike mass of agglomerate. Some patches of the limestone have high apatite content. The alkaline rock complex in the old volcanic neck at Sekulolo is about 3 miles in diameter, probably circular in outline, but it is almost completely covered by later tuffs. Nephelinitic, pyroxenic, and micaceous rock types are exposed in an arcuate ridge about 2 miles long, and fine needles of sodic hornblende occur in the granite near the complex, but carbonatite is not exposed.

<u>Premier diamond mine, Transvaal</u>: Carbonate dikes, regarded by Daly (1925) as essentially magmatic in origin, cut the kimberlite of the Premier diamond mine, Transvaal. The dikes are evenly fine-grained, composed of calcite, dolomite, magnetite, serpentine, apatite, sphene, periclase, and magnesium hydrate.

<u>Pretoria salt-pan, Transvaal</u>: Wagner (1922) favored an igneous origin for the carbonate material that makes up the groundmass of certain breccias

found in the Pretoria salt-pan of South Africa. The breccia fragments, brought up from unknown depth by explosive volcanic action, include 4 types of syenite, pyroxene foyaite porphyry, anorthoclase-rich porphyry, fine-grained lamprophyric augitite, quartzite, sandstone, and typical Bushveld norite. The dolomitic breccia is composed of rounded to angular lumps of chlorite schist to 2½ inches in diameter, smaller fragments of magnetite, cherty quartzite, and large irregular plates of chlorite, in a base of small particles of the same rocks and minerals. Some specimens contain radial aggregates of specularite, and thin stringers of calcite and specularite. The groundmass of the breccia is largely dolomite, calcite, and dolomitic ankerite, with minor chlorite, quartz, magnetite, leucoxene, apatite, and pyrite. Wagner suggests that these dolomitic rocks are of the nature of an injection breccia formed by the incorporation of fragments of chlorite schist and chloritic quartzite in a magmatic dolomite-calcite-biotite-magnetite-pyrite-apatite rock, and suggests that CO_2 formed by the dissociation of magmatic carbonates may have played an important part.

Jacupiranga, Sao Paulo, Brazil: Carbonate rocks and alkalic dike rocks are associated with the magnetite deposits of Jacupiranga, Brazil (Derby, 1891). The dike rocks include such types as augite syenite, jacupirangite, foyaite, and nephelinite. A long narrow ridge of limestone, which Derby presumed to be of Cambrian age, occurs near the center of the jacupirangite area, but the contact of limestone with the surrounding rocks could not be observed. The limestone is a white, generally coarsely crystalline marble, in places heavily charged with apatite and large perfect crystals of magnetite. Large flakes of hydrated biotite with perfect crystal outlines appear to form a primary constituent of the rock, and allanite occurs in the limestone near its border.

Kola Peninsula, Russia: Examples of the concentration of uncommon elements in alkalic rock provinces are found in Russia. In the Khibine and Lovozero tundras on the Kola Peninsula, according to Fersman (1937), remarkable concentrations of such elements as P, Ti, Sr, Zr, rare earths, F, Nb, Mo, Th, Ta, Y, and V are associated with alkaline rock complexes. Fersman lists 110 minerals that have been found in this region. Certain of these minerals are characteristic of certain rock types formed in the process of cooling of the plutons. The major part of the uncommon minerals are in pegmatites which occur chiefly as small pockets or streaks, closely connected with nepheline syenites.

Azov Sea region, Russia: In the Azov Sea region, the Petrovsko-Gnutovo fluorite-carbonate vein is a fissure filling in alkaline hornblende granite, according to Kuzmenko (1940). The dark minerals of the alkaline granite are aegirine and amphibole of the crossite-crocidolite type. Syenites and rock types transitional with the granite are additional differentiates of the alkaline magma.

The vein has sharp contacts and is 0.3-2.85 meters thick. It is composed of carbonates, fluorite, quartz, chalcedony, sphalerite, galena, chalcopyrite, pyrite, argentite, cerussite, covellite, limonite, and oxides of manganese. Brownish-pink parisite constitutes 25 to 75 percent of parts of the vein, and the average is assumed to be 8 to 10 percent. The rock analyzed was found to be rich in cerium oxide and $(La, Di)_2O_3$, with small amounts of $(Y, Er)_2O_3$ and ThO_2. Formation of the vein is interpreted by Kuzmenko as due to hydrothermal activity, the rare earths having been concentrated in the residual solutions during differentiation of the alkaline magma.

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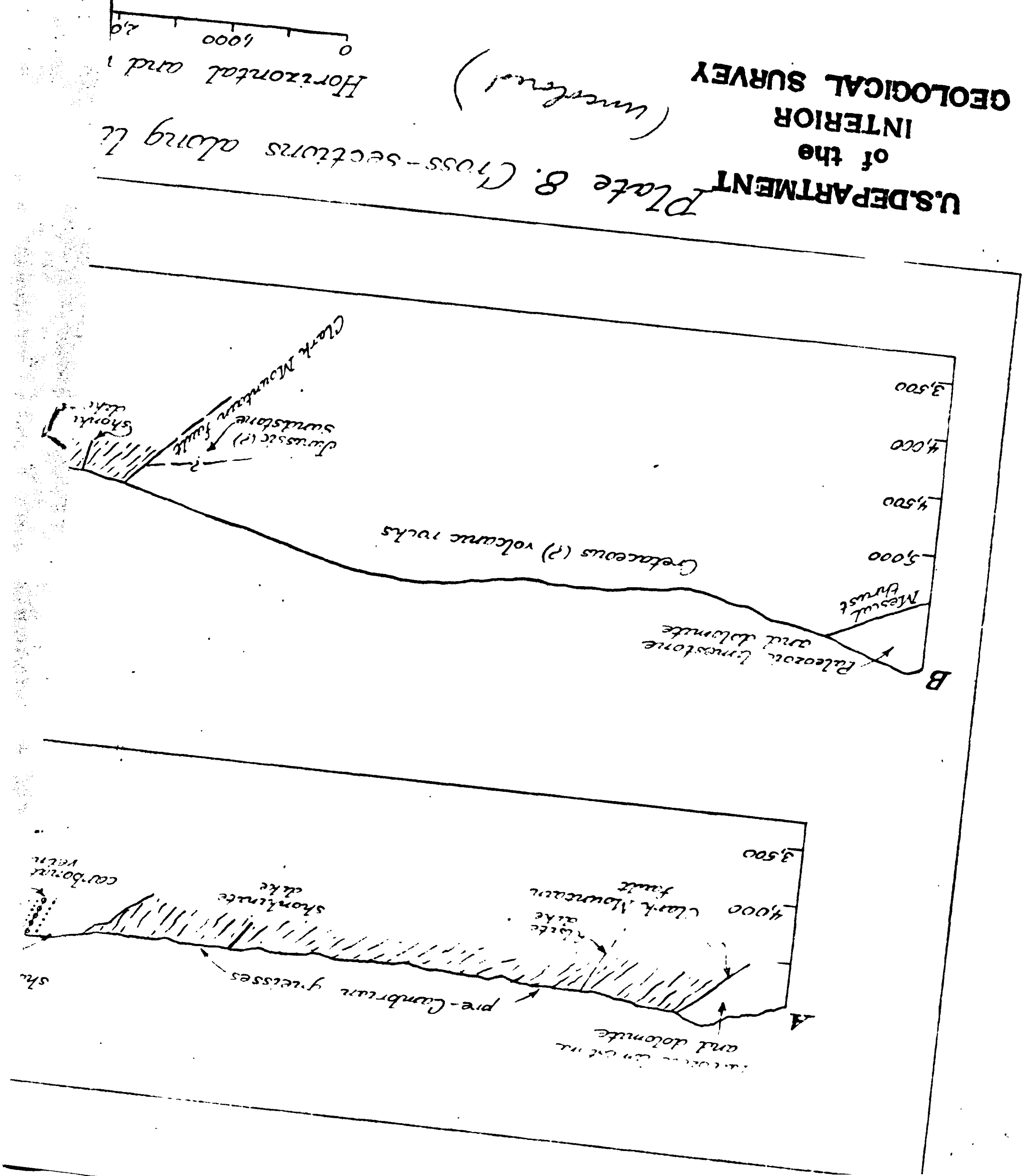

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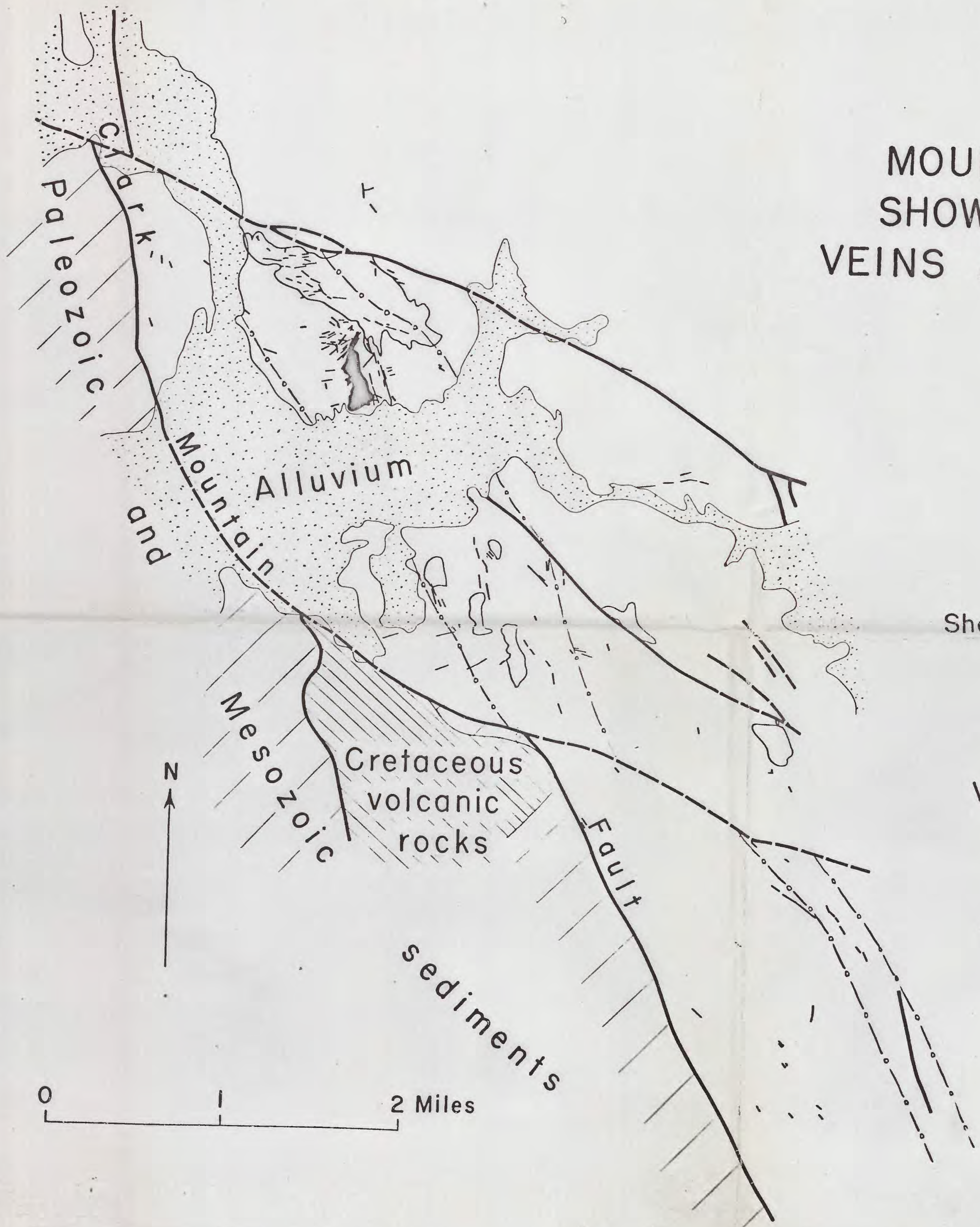
Plate 6.

MOUNTAIN PASS DISTRICT, SHOWING DISTRIBUTION OF VEINS AND CARBONATE ROCKS



EXPLANATION

Shonkinite, syenite, and granite

Veins and carbonate rocks

Fault

Outline of area containing principal rare earth deposits known in 1951

This map is preliminary and has not been edited or reviewed for conformity with U. S. Geological Survey standards and nomenclature.

Plate 6