3. THE MOUNTAIN PASS RARE-EARTH DEPOSITS [1]

By J. C. Olson [2] and L. C. Pray [3]

Introduction. Rare-earth minerals were discovered near Mountain Pass in northeastern San Bernardino County, Calif., in April 1949, and in the following year the Sulphide Queen carbonate body was found. This body is the world's greatest known concentration of rare-earth metals with a tonnage larger than the total of all rare earths used in the world prior to 1950. The rare earths in the Mountain Pass district are chiefly cerium, lanthanum, and neodymium. These elements occur principally in bastnaesite, a rare-earth fluocarbonate, heretofore reported from only about 10 localities in the world.

The bastnaesite was discovered in samples from Mountain Pass obtained by H. E. Woodward and Clarence Watkins of Goodsprings, Nev., and its identity was established in laboratory studies by E. T. Schenk of the U. S. Bureau of Mines and D. F. Hewett of the U. S. Geological Survey. Subsequent prospecting by individuals and geologic investigations by the U. S. Geological Survey resulted in the discovery of bastnaesite in the Sulphide Queen carbonate body and numerous other deposits in a belt 6 miles long.

Investigations by the U. S. Geological Survey since 1949 (Olson et al., in preparation) include detailed mapping of the site of the initial discovery—the Birthday claims—by L. C. Pray and W. N. Sharp; geologic mapping of the district by J. C. Olson; detailed mapping of the Sulphide Queen carbonate body and several smaller deposits by D. R. Shawe and W. N. Sharp; and laboratory mineralogic investigations by H. W. Jaffe.

General Geology. The area of known rare-earth mineral occurrences in the Mountain Pass district lies within a belt of pre-Cambrian metamorphic and igneous rocks that is bounded on the east and south by the alluvium of Ivanpah Valley. The west boundary is the Clark Mountain fault, a west-dipping normal fault along which the Paleozoic sedimentary rocks and Mesozoic sedimentary and volcanic rocks on the hanging wall have been displaced as much as 12,000 feet relative to the pre-Cambrian rocks of the footwall (Hewett, in preparation). The north boundary is formed by a conspicuous transverse fault that cuts the Clark Mountain fault and is just a few hundred feet north of the Birthday shaft. Although pre-Cambrian rocks crop out north of this fault for 10 miles, they are not known to contain any rare-earth mineral deposits or alkalic igneous rocks.

The pre-Cambrian metamorphic complex consists of hornblende and mica gneisses and schists, locally containing sillimanite or coarse garnet; biotite granite gneiss with coarse rectangular or eye-shaped feldspar grains; light-colored granitic augen gneiss and associated pegmatites; and minor dike rocks of mafic to intermediate composition. All these pre-Cambrian metamorphic rocks have a foliation that strikes generally north to northwest—about parallel to the general trend of the Clark Mountain fault—and dips are 50-80° W. in most places. Units based upon the relative proportions of the various pre-Cambrian rock types have been recognized but are not delineated on the accompanying map (pl. 1).

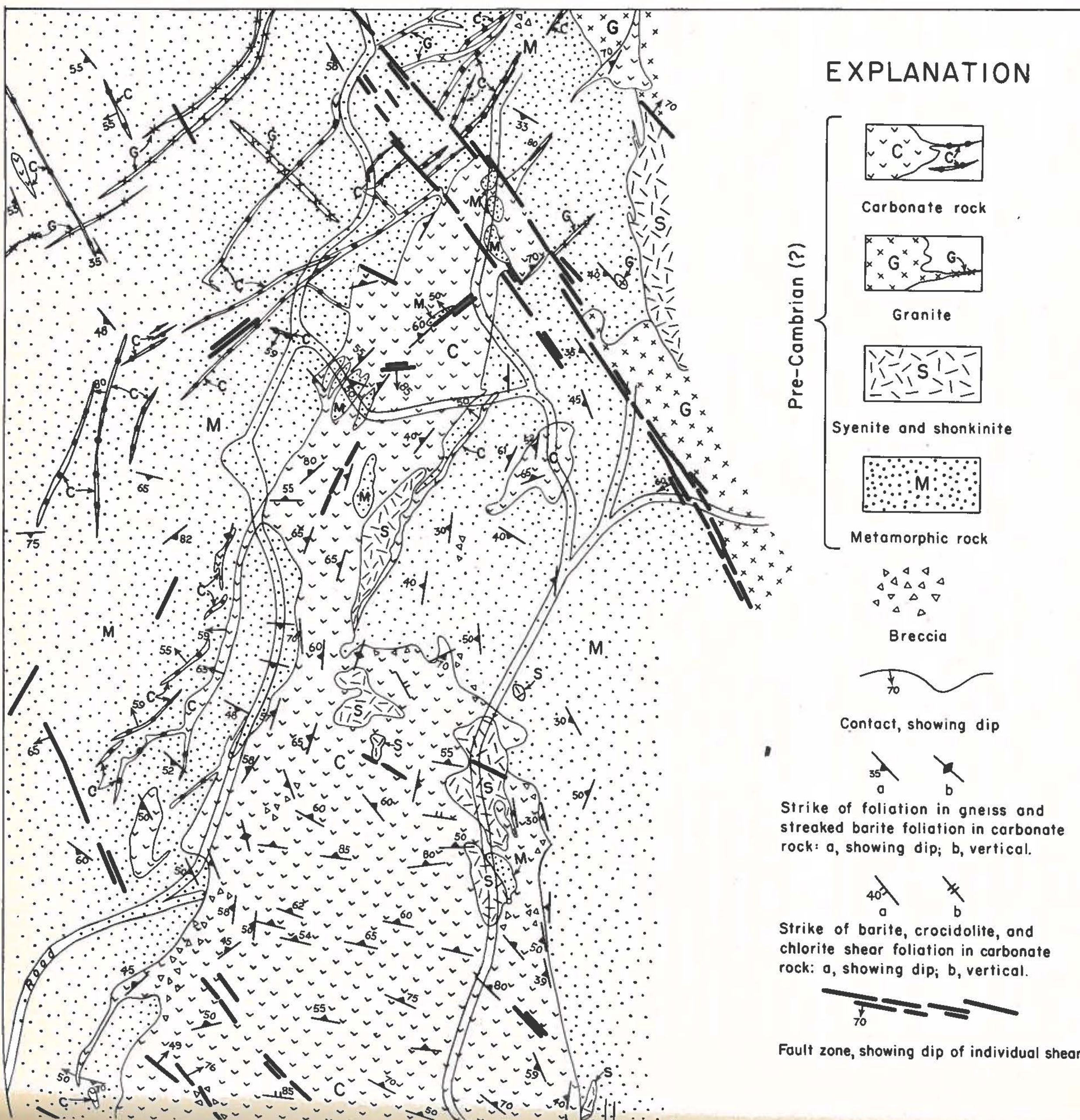
Igneous Rocks. The metamorphic complex is intruded by igneous rocks of two groups. The older group consists of potash-rich rocks which range in composition from shonkinite through syenite to granite. These rocks are related to the carbonate and rare-earth mineralization and are considered pre-Cambrian. The second group, which includes dikes of andesite, basalt, and rhyolite, is distinctly younger and is probably of Tertiary age. Most of the potash-rich dikes trend northwest, parallel to the regional foliation of the metamorphic complex, whereas the younger andesitic dikes trend generally east.

The potash-rich intrusive rocks occur in several hundred thin dikes and in seven larger intrusive bodies. Most dikes appear to dip southwest at moderate to steep angles, but exceptions are numerous among the thinner dikes. The largest intrusive body, near the Sulphide Queen mine, is composed largely of shonkinite and mafic syenite and is about 6,000 feet long and 1,800 feet wide. Of the other six intrusive bodies, the two nearest U. S. Highway 91 are leucosyenites, with 2 or 3 percent quartz; the southeasternmost is chiefly red granite; and the other three are composite shonkinite-syenite bodies.

The shonkinite is the oldest of the potash-rich rocks, and the syenite, quartz syenite, and granite are successively younger. However, the youngest of the potash-rich rocks are dikes of fine-grained shonkinite. Thin dikes of all the potash-rich rocks occur throughout the district and in general are finer grained than the same rocks in the seven larger intrusive bodies.

The shonkinite is typically a coarse-grained rock composed of about equal amounts of distinctive grayish-red microcline, green

[1] Publication authorized by the Director, U. S. Geological Survey. Contribution No. 660, Division of the Geological Sciences, California Institute of Technology.
[2] Geologist, U. S. Geological Survey, Denver, Colo.
[3] Assistant Professor of Geology, California Institute of Technology, and geologist, U. S. Geological Survey, Pasadena, Calif.


EXPLANATION
Pre-Cambrian (?)
C
Carbonate rock
G
Granite
S
Syenite and shonkinite
M
Metamorphic rock
Breccia
70
Contact, showing dip
35
a
b
Strike of foliation in gneiss and streaked barite foliation in carbonate rock: a, showing dip; b, vertical.
40
a
b
Strike of barite, crocidolite, and chlorite shear foliation in carbonate rock: a, showing dip; b, vertical.
70
Fault zone, showing dip of individual shear
Road

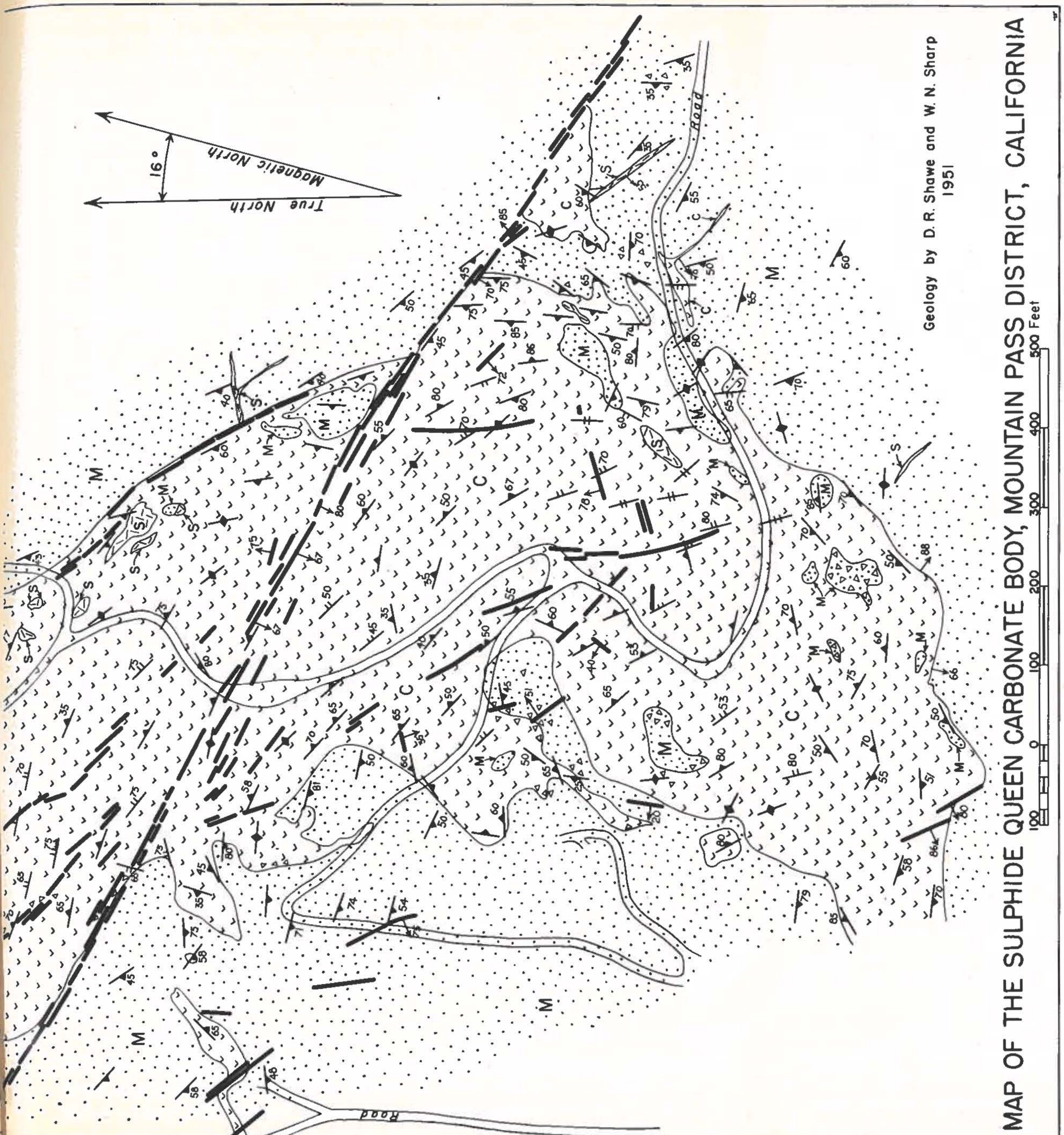

MAP OF THE SULPHIDE QUEEN CARBONATE BODY, MOUNTAIN PASS DISTRICT, CALIFORNIA
Geology by D. R. Shawe and W. N. Sharp
1951
100 0 100 200 300 400 500 Feet
True North
Magnetic North
16°
Road
Road

FIGURE 1.

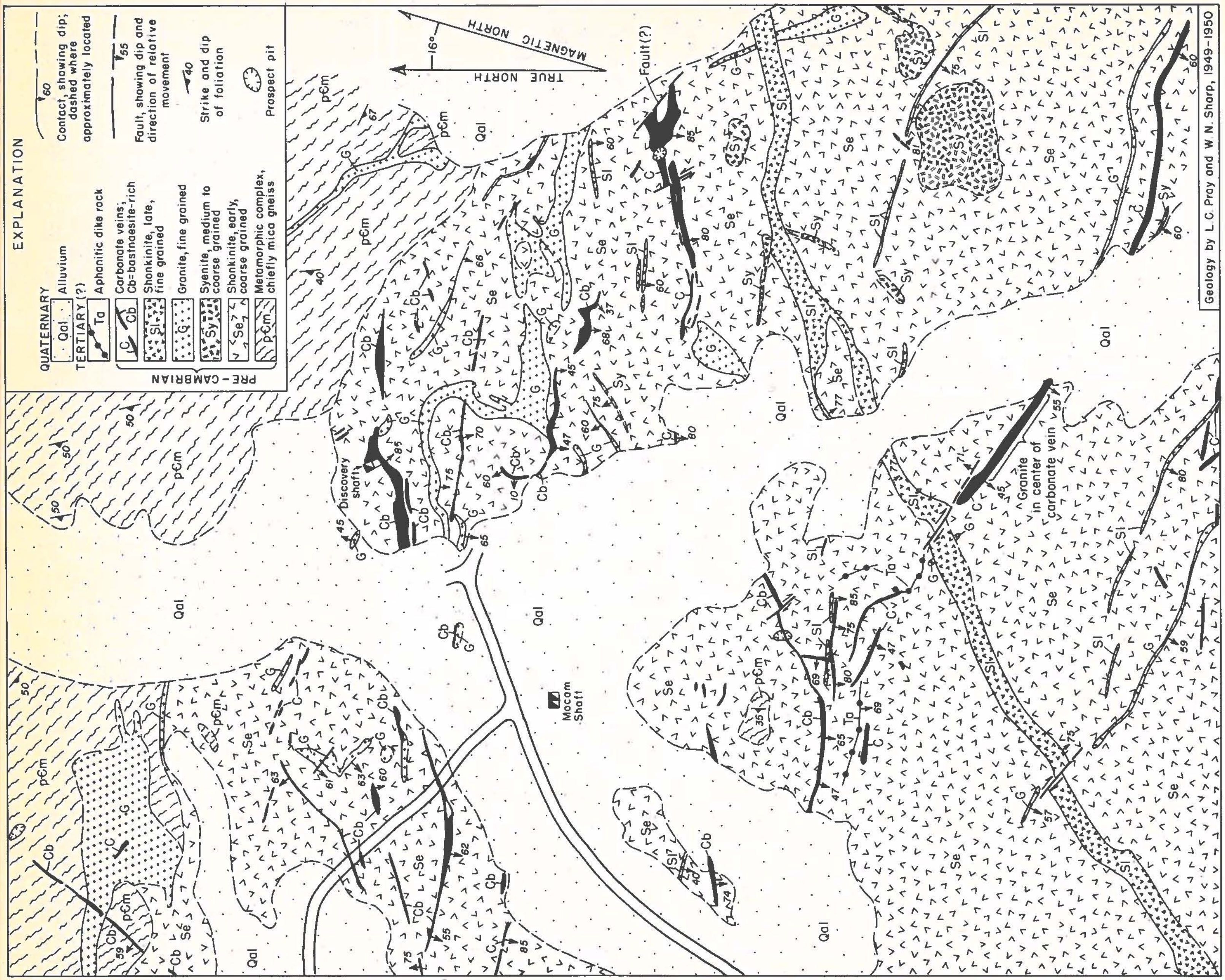


FIGURE 2. Map of the eastern part of the Birthday claim area, Mountain Pass district.

augite, and biotite. With decrease of pyroxene and biotite and increase in potash feldspar, the shonkinite grades into syenite, and this in turn grades into granite with 10 to 40 percent quartz and less than 10 percent mafic minerals. Amphiboles are common constituents of the potash-rich rocks, and sodic varieties such as riebeckite, arfvedsonite, and sodic hornblende are widespread. Aegirine and aegirine-augite occur in feldspar-rich pockets within the shonkinite. The fine-grained shonkinitic dikes differ mineralogically from the older coarse-grained shonkinite: they contain several percent quartz, more sodic amphibole or aegirine-augite, and less augite. All the potash-rich rocks are interpreted as products of a single period of intrusive activity, a period during which the temperatures of the invaded rock appear to have progressively decreased, as shown by fine-grained "chilled" borders on some of the youngest potash-rich rocks.

The genetic affinity among the various potash-rich rocks is indicated by field and petrologic relationships and by chemical and spectrographic analyses. Analyses of two shonkinites, one coarse syenite, one fine-grained granite, and one shonkinitic dike rock show a range in K_2O content from 7.0 to 11.2 percent, compared to a range in Na_2O content of 0.26 to 1.4 percent. Analyses of these same samples also show an abnormally high content of barium and strontium oxides (0.26 to 1.2 percent) and of the cerium group of rare earths (0.03 to 0.4 percent La), indicating the genetic relationship of potash-rich rocks to the carbonate rocks.

The carbonate rocks cut and are therefore younger than the potash-rich igneous rocks, although one possible exception was noted on the Birthday claims where a thin vein appeared to be cut by a shonkinitic dike a few inches thick. Radioactive age determinations on monazite from the Sulphide Queen carbonate body of about 900 to 1,000 million years (Jaffe, H. W., in preparation) suggest a probable Proterozoic age for the rock. The potash-rich igneous rocks are older than the carbonate rock, though closely related, and thus are pre-Cambrian.

Many dikes of aphanitic to fine-grained rock, chiefly andesitic but ranging in composition from basalt to rhyolite, cut all the other rocks and on the basis of regional evidence are considered Tertiary(?) in age. These dikes are 1 foot to 20 feet thick, are vertical or dip steeply, and occur mostly in four swarms of east-trending dikes.

Carbonate Rocks. About 200 veins composed largely of carbonate minerals but commonly containing abundant barite and quartz have been mapped in the district. Most of these veins are 1 foot to 6 feet thick. They cut across the pre-Cambrian foliation and all the dike rocks. Some appear to have been emplaced in fractures in the shonkinite-syenite intrusives. One remarkable deposit, called the Sulphide Queen carbonate body because of its proximity of the old Sulphide Queen gold mine, is estimated to have at least 10 times the surface area of all the other carbonate veins exposed in the district. The Sulphide Queen carbonate body is 700 feet in maximum width, 2,400 feet long, and appears to dip to the west at a moderate angle. It is similar mineralogically to many of the veins in the district.

FIGURE 3. Outcrop of bastnaesite-rich vein on Birthday claims. Tabular bastnaesite crystals and whitish patches of barite weather out in relief above dominant calcite matrix.

The distribution of carbonate rocks and veins in the district is shown on the geologic map (pl. 1). 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 for about 5 miles from the southeast corner of the map area to the vicinity of the Birthday shaft. This belt is offset by several transverse faults and appears to be terminated by the transverse fault north of the Birthday shaft.

Although no large fault has been mapped in or parallel to the rare-earth and thorium belt, many small northwest-trending faults are exposed for short distances, and these contain local deposits of rare earths and thorium. The abundance and size of the carbonate bodies in the belt appear to be spatially related to the potash-rich intrusive rocks, for the greatest concentration is in and along the southwest side of the largest shonkinite-syenite body. Mineralized shear zones in this belt cut the shonkinite-syenite body and related dikes, as well as the 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 there was some circulation of mineralizing solutions after the faulting.

The dominant carbonate minerals, which constitute at least half of most veins, are calcite, dolomite, ankerite, and less commonly siderite. Barite is a widespread vein mineral, averaging 20 or 25 percent of the carbonate rock in the district and locally exceeding 65 percent. The barite contains variable amounts of strontium, and some barian celestite is present.

The rare-earth minerals thus far recognized include bastnaesite, parisite, monazite, allanite, sahamalite (Jaffe et al., 1953), and cerite. Of these the most abundant is bastnaesite, which constitutes 5 to 15 percent of much of the Sulphide Queen carbonate body and locally exceeds 60 percent.

Quartz occurs in the veins in various proportions, generally from 5 to 40 percent but ranging from nearly 0 to 100 percent. Other minerals found in the carbonate rocks include crocidolite, chlorite, biotite, phlogopite, muscovite, sphene, magnetite, hematite, goethite, galena, pyrite, chalcopyrite, tetrahedrite, malachite, azurite, cerussite, strontianite, aragonite, wulfenite, fluorite, apatite, and thorite.

Structural features of the Sulphide Queen deposit are shown in figure 1. Breccia fragments of older rocks such as gneiss, syenite, and carbonate rock are present locally in the Sulphide Queen carbonate body, chiefly near the walls, as well as in several other breccia veins. Some of the angular feldspathic wall-rock fragments in the Sulphide Queen carbonate body are but little rotated, but in other places aggregates of well-rounded fragments of several rock types indicate movement from their original positions in the country rock. The feldspathic fragments are typically coated with reaction rims of dark phlogopite or biotite.

A planar structure is evident in many of the carbonate deposits. Part of this layering or banding is apparently a primary feature of the veins. Part of the planar structure appears to be a foliation due to shearing and is generally parallel to the walls of the 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. These grains are very common in the Sulphide Queen carbonate body. The foliation and inclusions in this body and its discordance to the foliation of the gneissic wall rocks suggest that the carbonate mass was intruded into its present position.

Origin of the Deposits. The interpretation of the origin of the Mountain Pass rare-earth deposits involves three related features: the group of potash-rich igneous rocks ranging in composition from shonkinite to granite, the carbonate rock that occurs in the notable

FIGURE 4. Photomicrograph of tabular bastnaesite crystals in calcite matrix. (25x, plane polarized light)

Sulphide Queen carbonate body and in at least 200 thinner veins, and the exceptionally large concentration of rare-earth metals of the cerium group. These three features are associated spatially, and probably genetically, and are thought to have had their origin during a single geologic episode.

The association of alkalic igneous rocks and carbonate rocks has been reported from many areas of the world. Among those which appear to be somewhat similar to Mountain Pass are Alnö, Sweden; Fen, Norway; several localities in South Africa; Magnet Cove, Ark.; and Iron Hill, Colo. The large amount of carbonate rock in these areas has been interpreted in several ways, principally as either a magmatic product or as inclusions of sedimentary limestone. At Mountain Pass, as in most of the other areas, there is no known sedimentary limestone in the invaded pre-Cambrian rocks. The Sulphide Queen carbonate body is enclosed in pre-Cambrian gneisses rather than in an igneous rock.

Geochemical data from many parts of the world indicate that the cerium group of rare earths tend to be associated with alkalic igneous rocks. The rare-earth elements in part occur in small amounts in the major rock-forming minerals. They also form independent minerals, such as monazite or allanite, disseminated as accessory constituents in various igneous rocks. These elements are also selectively concentrated in residual products of crystallization, owing in part to their relatively large ionic radii, as shown by the common occurrence of rare-earth minerals in pegmatites. Of the known occurrences of bastnaesite, the primary deposits occur in pegmatites, in contact zones, or in veins closely associated with igneous rocks.

The most plausible mode of origin of these features at Mountain Pass is that the materials forming the carbonate rocks were derived largely by differentiation from the same magmatic source that supplied the potash-rich dike rocks. This hypothesis harmonizes with the evidence of the foliation, breccia fragments, and discordance of the Sulphide Queen carbonate body; with the consistent sequence of emplacement and the close association of the potash-rich dike rocks and carbonate veins in the district; and with the remarkable concentrations of certain rare elements.

LITERATURE CITED

Hewett, D. F., (in preparation), Geology and mineral resources of the Ivanpah Quadrangle: U. S. Geol. Survey Prof. Paper.

Jaffe, H. W., Meyrowitz, R., and Evans, H. T., 1953, Sahamalite, a new rare earth carbonate mineral: Am. Mineralogist, vol. 38, p. 741-754.

Olson, J. C., Shawe, D. R., Pray, L. C., and Sharp, W. N., (in preparation), Rare-earth mineral deposits of the Mountain Pass district, San Bernardino County, California: U. S. Geol. Survey Prof. Paper 261.