Radioactive Rare-Earth Deposit at Scrub Oaks Mine, Morris County New Jersey

By HARRY KLEMIC, A. V. HEYL, Jr., A. R. TAYLOR, and JEROME STONE

CONTRIBUTIONS TO ECONOMIC GEOLOGY

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By HARRY KLEMIC, A. V. HEYL, JR., A. R. TAYLOR, and JEROME STONE

ABSTRACT

A deposit of rare-earth minerals in the Scrub Oaks iron mine, Morris County, N. J., was mapped and sampled in 1955. The rare-earth minerals are mainly in coarse-grained magnetite ore and in pegmatite adjacent to it. Discrete bodies of rare-earth-bearing magnetite ore apparently follow the plunge of the main magnetite ore body at the north end of the mine. Radioactivity of the ore containing rare earths is about 0.2 to 0.6 milliroentgens per hour.

The principal minerals of the deposit are quartz, magnetite, hematite, albite-oligoclase, perthite and antiperthite. Xenotime and doverite aggregates and bastnaesite with intermixed leucoxene are the most abundant rare-earth minerals, and zircon, sphene, chevkinite, apatite, and monazite are of minor abundance in the ore. The rare-earth elements are partly differentiated into cerium-rich bastnaesite, chevkinite, and monazite, and yttrium-rich xenotime and doverite. Apatite, zircon, and sphene contain both cerium and yttrium group earths.

Eleven samples of radioactive ore and rock average 0.009 percent uranium, 0.062 percent thorium, 1.51 percent combined rare-earth oxides including yttrium oxide and 24.8 percent iron. Scatter diagrams of sample data show a direct correlation between equivalent uranium, uranium, thorium, and combined rare-earth oxides. Both cerium- and yttrium-group earths are abundant in the rare-earth minerals.

Radioactive magnetite ore containing rare-earth minerals probably formed as a variant of the magnetite mineralization that produced the main iron ore of the Scrub Oaks deposit. The rare-earth minerals and the iron ore were deposited contemporaneously. Zircon crystals, probably deposited at the same time, have been determined by the Larsen method to be about 550 to 600 million years old (late Precambrian age).

Uranium, thorium, and rare-earth elements are potential byproducts of iron in the coarse-grained magnetite ore.

INTRODUCTION

A deposit of radioactive rare-earth minerals in the Scrub Oaks mine in the Dover magnetite district, Morris County, N. J. (fig. 1), was disclosed in 1954 after a specimen of radioactive rock found on the 5th level of the mine by Charles Weiler and Edward Osetek of the Alan Wood Steel Co. was given to the senior author and analyzed in the U. S. Geological Survey laboratories. Bastnaesite,

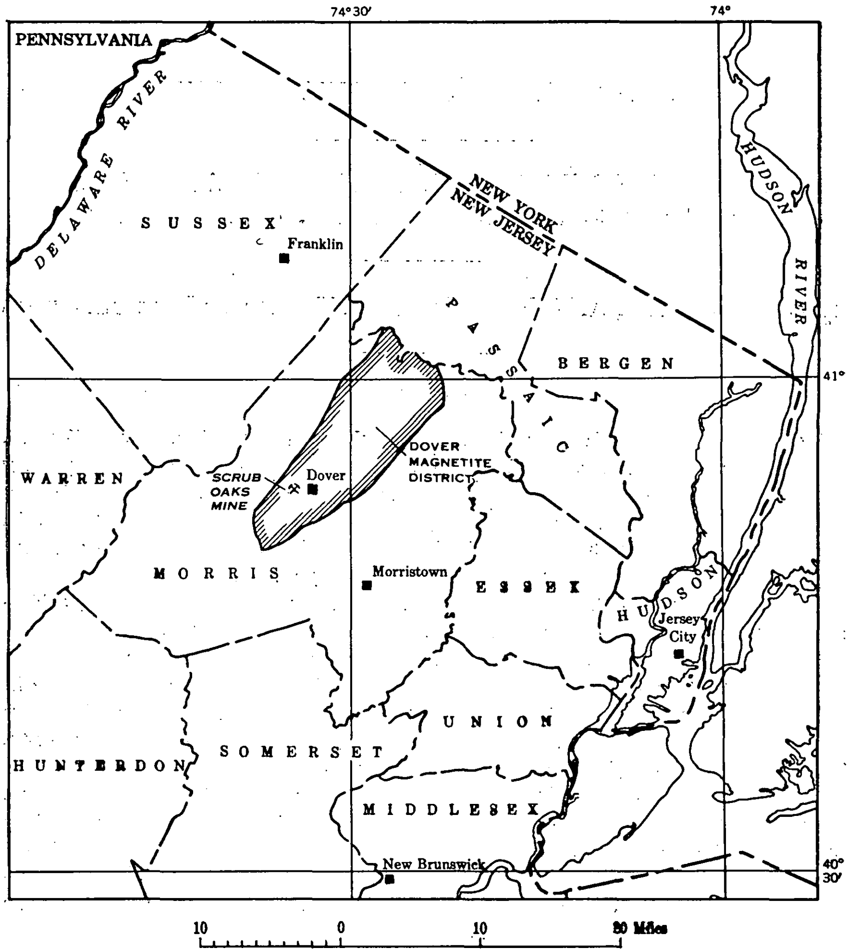

FIGURE 1.—Index map showing location of Scrub Oaks mine in Dover magnetite district, Morris County, N. J.

xenotime, and doverite, a new mineral species, were identified in the rock (Smith and others, 1955, p. 31).

The deposit was studied by the authors as part of the Geological Survey program of reconnaissance for radioactive materials made on behalf of the Division of Raw Materials, U. S. Atomic Energy Commission. Radioactive coarse-grained magnetite ore near the north end of the 5th, 6th, and 7th levels in the mine contains a small percentage of cerium-rich, and yttrium-rich rare-earth minerals. Uranium, thorium, and rare-earth elements are potential byproducts of iron in this ore.

In June 1955, part of the mine near the north end of the 6th level where radioactive rock occurs, was examined by the writers. The distribution of radioactive rock was mapped in part of one stope on the 6th level and in the sublevel below it (pl. 1). Samples of radioactive rock were taken from the stope and the sublevel for analyses. Diamond-drill core was examined from holes drilled from the sublevels on the 6th and 7th levels.

The authors are indebted to W. P. Schenck, superintendent of the Mining Division of the Alan Wood Steel Co. for his friendly cooperation during these investigations. Charles Weiler and Edward Osetek made the discoveries that led to disclosure of the deposit and furnished information about the occurrence of the ore. Descriptions of the geology of the Dover magnetite district and of the Scrub Oaks mine by Paul K. Sims (1953, 1958) are quoted at length. Sims also made many useful suggestions after reviewing this report. William L. Smith of the Geological Survey made many helpful suggestions concerning the mineralogy of the deposit. All analytical work was done by personnel of the U. S. Geological Survey.

GEOLOGY

The Scrub Oaks mine is in the Dover magnetite district in the New Jersey Highlands. The geology of the district has been described by Sims (1958). Information from his reports, which include the results of his own investigations and those of previous workers in the area, is used here in describing the geologic environment of the rare-earth deposit.

The New Jersey Highlands are in the Reading prong of the New England physiographic province. This is an area of northeastward-trending ridges and valleys with altitudes ranging from 500 to 1,100 feet in the Dover district. Bedrock in the area surrounding the Scrub Oaks mine is of Precambrian age and includes metasedimentary rocks, mixed rocks, and igneous rocks. Quaternary glacial and alluvial deposits conceal the bedrock in much of the area.

ROCK UNITS

High-grade metamorphic rocks derived from calcareous and quartzose sedimentary rocks are the oldest rocks in the district. The principal types of metamorphic rocks in the area near the Scrub Oaks mine are biotite-quartz-feldspar gneiss and oligoclase-quartz-biotite gneiss. According to Sims, the oldest igneous rocks in the district are quartz diorite and diorite. They were emplaced early in the period of Precambrian orogeny that deformed the metasedimentary rocks. A wide variety of granitic rocks were emplaced later in the period. Albite-oligoclase granite is the oldest of these and hornblende granite and related facies the youngest. Sims' descriptions (1953, p. 259–260) of the granitic rock units in the area adjacent to the Scrub Oaks mine follow:

ALBITE-OLIGOCLASE GRANITE

The granite is a buff to red, medium-grained rock that is composed almost entirely of plagioclase (An_8–An_{15}) and quartz. Muscovite is a common accessory mineral. A few percent of augite, hornblende, and biotite, derived from contamination by assimilation, are present locally, particularly near mafic inclusions.

Small irregular bodies of albite granosyenite pegmatite are associated with the granite, particularly at the Scrub Oaks and Beach Glen mines * * *

HORNBLENDE GRANITE

Hornblende granite is the most abundant facies of the granite, constituting about 60 percent of the granitic rocks. Hornblende granite forms sheets, from 1,000 to about 5,000 feet wide, and phacoliths of moderate size * * *

The hornblende granite is a buff, medium-grained, but locally coarse grained, equigranular, uniform gneissoid rock. It weathers to brown, tan, or white. The granite is composed of 35 to 65 percent microperthite, 6 to 35 percent oligoclase, about 25 percent quartz, and 5 to 10 percent hornblende * * *

ALASKITE

Bodies of alaskite are found at and near the contacts of hornblende granite and country rock, in mixed-rock zones, and along the anticlinal crests of large folds. Alaskite occurs in close proximity to nearly all ore deposits; it forms an envelope around the oligoclase-quartz-biotite gneiss layer that contains many of the important deposits * * *

The alaskite is composed essentially of microperthite and quartz. Mafic minerals, principally hornblende, augite, and biotite, constitute less than 5 percent of the rock * * *

MICROANTIPERTHITE GRANITE

Narrow linear bodies of microantiperthite granite are found in places in the contact zones between alaskite and quartzose country rocks. The granite differs mineralogically from alaskite principally in containing microantiperthite rather than microperthite as the chief feldspar. Much of it contains a few percent of augite or hornblende * * *

GRANITE PEGMATITE

Granite pegmatite forms irregular bodies with ill-defined boundaries in granite, and sharply defined conformable or crosscutting bodies in country rocks. It is common, but usually not abundant, except near ore deposits.

The pegmatites are simple, nearly homogeneous bodies composed of perthite, quartz, and sodic plagioclase, with accessory magnetite, allanite, and zircon. Locally large crystals of hornblende or augite, as much as 6 inches in length, derived from contamination, are present * * *

STRUCTURE

The metasedimentary rocks in the district are folded isoclinally. The folds are generally overturned to the west, and their axes plunge to the northeast. The igneous rocks are synkinematic intrusive masses (Sims, 1953, p. 265) that were emplaced as conformable sheets in the sedimentary rocks during both the early and late stages of folding. Pegmatites were emplaced near the close of deformation and are mostly undeformed.

Precambrian rocks including magnetite deposits are cut by many faults. Most of the faults have relatively small displacements, but some, particularly those that are transverse to structural trends, have displacements as great as a few hundred feet. The transverse faults are normal faults that strike northwest and dip south.

SCRUB OAKS MINE

The Scrub Oaks iron mine is in the southern part of the Dover magnetite district about 2 miles west of Dover. The mine is owned and operated by Alan Wood Steel Co. of Conshohocken, Pa. and is currently active (1957). The mine workings consist of a four-compartment shaft and six working levels that average about 5,000 feet in length. The north end of the 6th level had not been developed at the time of Sims (1953) study. The 7th and 8th levels are now being developed. The shaft is inclined 55° SE., and the working levels are 250 feet vertically apart. The levels are connected by inclined raises. Sublevels, roughly parallel to and about 30 feet above the main haulage levels, extend the length of the mine. In previous workings the sublevels were driven in the ore body, but at the north end of the 6th level and in the 7th and 8th levels the sublevels are in the footwall at or near the footwall-ore contact.

GEOLOGY OF THE MAIN ORE BODY

The Scrub Oaks iron ore deposit is a tabular body of magnetite-hematite ore in albite-oligoclase granite flanked by alaskite. Locally, part of the albite-oligoclase unit includes pegmatite. The ore occupies granulated and partly recrystallized zones in the country rock. The ore body and the country rock trend N. 33° E. and dip 55° SE. and the deposit plunges 28° N. 52° E. (Sims, 1953, p. 299), parallel to the lineation in the country rock. In detail the ore body splits or pinches and swells, and locally changes dip and strike. The ore zones mapped in the stope near the north end of the 6th level (pl. 1) are irregular in outline.

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IRON ORE DEPOSIT

Sims (1953, p. 299–300) describes the ore as follows:

> Magnetite is the chief ore mineral; primary crystalline hematite constitutes about 15 percent of the ore, but ranges from about 1 percent to at least 30 percent locally. The hematite is abundant in 1,586 and 1,587 stopes (no. 5 level), where it forms about 50 percent of the ore; and at the head of 70 manway raise on no. 4 level. Elsewhere in the mine hematite generally constitutes less than 5 percent of the ore. To judge from its distribution the hematite-rich ore seems to be closely related to the axis of a prominent roll.
>
> The nonmagnetic iron ore is locally referred to as martite. There is no evidence, however, either megascopically or microscopically, that this ore is martite; instead, the nonmagnetic ore is hematite. Polished sections of hematite ore indicate that the hematite forms distinct coarse granules that exhibit marked twinning. In part hematite forms rims around magnetite; it is seen also to form veins in magnetite.
>
> The gangue minerals, which constitute an integral part of the ore, are chiefly albite and quartz, unreplaced remnants of the granite host rock. Several other minerals are present in the ore * * * These are apatite, rutile, tourmaline, calcite, muscovite, and pumpellyite. With the exception of some of the apatite these accessory minerals are later than the magnetite.
>
> The run-of-the-mine ore has an average iron content of about 27 percent and a phosphorus content of about 0.075 percent. The concentrate is of Bessemer grade.

Most of the Scrub Oaks iron ore is medium to fine grained according to the classification proposed by Teuscher (Johannsen, 1939, p. 31). Grains in these size categories range from about 0.3 to 3.3 millimeters in diameter. Some of the ore, however, is coarse grained. In milling, the ore is crushed to minus 8 mesh and finer in order to recover a high percentage of the iron in a suitable concentrate (Roche and Crockett, 1933, p. 273–277).

RARE-EARTH MINERAL DEPOSIT

Much of the rare-earth mineral deposit in the Scrub Oaks mine can be considered a part of the magnetite ore body. The rare-earth minerals commonly occur in coarse-grained magnetite ore, in magnetite-rich stringers, and in pegmatite adjacent to the magnetite ore in microantiperthite granite and alaskite country rock.

GENERAL CHARACTER AND APPEARANCE

The magnetite ore containing rare earths generally can be recognized by the presence of coarse-grained magnetite and by brick-red aggregates of the rare-earth minerals xenotime and doverite. The aggregates of xenotime and doverite resemble coarse-grained red feldspar that occurs at places in the country rock, but they can be distinguished from the feldspar by the absence of smooth cleavage surfaces. Light-gray and gray-black rare-earth minerals are abundant in some parts of the ore with only a small amount of the red aggregates.

Other rare-earth rocks have been found in the mine near the coarse-grained magnetite ore, but not much is known about them. Specimens of rock that may be vein quartz, with abundant zircon, doverite, and hematite were obtained from the 5th level of the mine; and a sample of radioactive, fine-grained, albite-oligoclase granite gneiss with antiperthite, much accessory magnetite, and discrete subhedral grains of rare-earth minerals was obtained from near the north end of the 7th level of the mine.

RELATION OF DEPOSIT TO MAIN IRON ORE BODY

The spatial relations of the rocks that contain rare-earth minerals to barren parts of the main magnetite ore body has not been completely determined. In general, the magnetite ore containing rare-earths is in discrete but irregular-shaped bodies near the top rock[1] of the main ore body, but in places the rare-earth-bearing ore is several hundred feet below the iron ore-top rock contact. The rare-earth deposit apparently follows the plunge of the main iron ore body, but continuity between bodies of rare-earth ore on different levels in the mine has not been determined. Rare-earth minerals and magnetite occur in pegmatite in the top rock adjacent to rare-earth iron ore. In the 1690 stope at the north end of the 6th level of the mine (pl. 1) the coarse-grained magnetite ore containing rare-earth minerals is separated from fine-grained magnetite ore that is more typical of the Scrub Oaks deposits by a 2- to 10-foot septum of hornblende granite country rock. The boundaries between the rock units are sharp. Within the rare-earth deposit, contacts between the coarse-grained magnetite ore and pegmatite are irregular and gradational in a few places and abrupt in others. In some exposures of coarse-grained magnetite ore the rare-earth minerals are distributed throughout the ore; in other exposures the minerals are spotty or are absent. Coarse-grained magnetite ore barren of rare-earth minerals has been found a few tens of feet downdip from the rare-earth-bearing magnetite ore. Coarse-grained ore containing rare-earth minerals also is found at about the same level as the coarse-grained barren ore, but approximately down the plunge of the ore body from the exposure in the raise (pl. 1).

Although the wall rock of the rare-earth deposit is mostly fine-grained microantiperthite granite (pl. 1), lenses of slightly coarser grained hornblende-plagioclase gneiss, alaskite, and bodies of granite pegmatite that are barren of rare-earth minerals occur locally within

[1] The top rock is defined by Sims (1953, p. 275) as the rock overlying the deposits in the plane of the ore.

the granite. The contacts of the rare-earth deposit with these wall rocks are sharply defined but irregular, with stringers and embayments from the deposit extending into the wall rock. Some stringers are alined at an acute angle to the general strike of the main magnetite ore body and of the wall rocks.

The rare-earth deposit in the part of the mine that has not been stoped out is exposed within an irregular parallelepiped-shaped zone that is about 30 feet wide and has a stope length of about 200 feet on the 6th level. The zone has a vertical extent of 500 feet, a length of about 600 feet along the dip and a pitch length of nearly 1,000 feet along the plunge of the main ore body. The deposit is reportedly exposed in the 1586 and 1589 stopes on the 5th level, and is exposed in the 1690 stope and adjacent sublevel of the 6th level, and in the sublevel of the 1799 stope on the 7th level (pl. 1). Similar rock was reportedly seen in higher levels by mine personnel, but no samples from the higher levels were obtained by the authors. For additional information concerning the mine workings the reader is referred to Sims (1958).

The extent of the rare-earth deposit in the 1589 stope before mining is not known, but coarse-grained ore similar to the deposit bearing rare earths was reported to have been noticeably abundant by Charles Weiler of the Alan Wood Steel Co. In the 1690 stope, which was opened but not mined out in 1956, the rare-earth magnetite ore is exposed for about 150 feet along strike (pl. 1). This ore has an apparent thickness of slightly more than 16 feet in parts of the stope; in other parts it thins to stringers only a few inches thick. The rare-earth deposit extends into pegmatite near the north end of the stope. This part of the deposit was above a draw point in the stope and only the part near the magnetite ore could be examined closely or sampled; therefore, no precise measurements of it were made.

On the sublevel of the 6th level (pl. 1), the rare-earth magnetite ore is exposed in two places about 150 feet apart along strike, and about 60 feet farther to the south along the sublevel a drill hole cut radioactive ore in the hanging wall.

In the sublevel of the 1799 stope of the 7th level, where little development work had been done as of January 1956, a band of magnetite ore 1½ to 2 feet wide containing rare-earth minerals has been exposed for a few feet. About 180 feet southwest of this exposure (pl. 1), a hole drilled into the hanging wall from the sublevel cuts two zones of coarse-grained, magnetite-rich rock containing rare-earth minerals. One zone is about a foot thick, the other is 3 feet. A zone of radioactive ore in a newly developed stope near the north end of the 7th level was described as about 10 feet wide and 60 feet long by S. J. Usinowicz (oral communication, 1957) of the Alan Wood Steel Co. The zone extended along the ore body on the hanging-wall side of the stope. Within the zone, a band of ore containing abundant rare-earth minerals was 3 to 4 feet wide and the remainder of the zone contained a smaller percentage of rare-earth minerals.

The 8th level has not been extended far enough to determine whether the ore continues below the 7th level.

RADIOACTIVITY

The rare-earth deposit in the Scrub Oaks mine is significantly more radioactive than the typical iron ore and country rock. Background radioactivity in barren rock or in iron ore devoid of rare-earth minerals in the 6th level and sublevel is about 0.015 milliroentgens per hour, as measured in the center of the passageways using a scintillation counter carried about waist high. Locally, readings are as high as 0.10 mr per hour in pegmatitic rock and 0.05 mr per hour in the albite-oligoclase granite country rock.

In passageways that cut through the rare-earth magnetite ore, the radioactivity is generally a little greater than 0.1 mr per hour and may be as much as 0.2. With the scintillation counter in contact with the ore the radioactivity is commonly between 0.2 and 0.6 mr per hour. In the raise in the 1690 stope, readings as high as 0.95 mr per hour were obtained on the face of the ore. The radioactivity was 0.15 mr per hour or greater for 25 feet along one side of the raise and 0.75 to 0.95 mr per hour for 15 feet of this length. In the sublevel of the 6th level, readings of 0.2 to 0.6 mr per hour were obtained along 45 feet of the roof of the sublevel, and readings of 0.2 to 0.45 mr per hour were obtained along the walls for a length of about 33 feet. Pegmatitic rock containing coarse red feldspar locally present within this ore zone is much less radioactive than the ore.

In all places where the coarse-grained rare-earth-bearing ore was examined the radioactivity at the face of the ore was 0.1 mr per hour or greater. Where the geometry of surfaces of ore is such that it raises the background radioactivity appreciably, a reading of 0.15 or 0.2 mr per hour on a scintillation counter probably is indicative of ore limits. As the country rock adjacent to the ore appears to be almost barren of radioactive minerals, it has a low radioactivity.

ANALYTICAL DATA

Chemical analyses for uranium, thorium, total rare earths (including yttrium) and iron, and radioactivity measurements of the same samples are reported in table 1. Eleven samples of radioactive ore and rock average 0.009 percent uranium, 0.062 percent thorium (0.071 percent ThO_2), 1.51 percent combined rare-earth oxides including yttrium oxide (Y_2O_3), and 24.8 percent iron (35.5 percent Fe_2O_3). Scatter diagrams of sample data show a direct correlation between equivalent uranium, uranium, thorium, and combined rare-earth oxides. Both cerium- and yttrium-group earths are abundant in the rare-earth minerals. The grab samples consisted of a few pounds of rock that appeared to be representative of the rock face from which they were taken. The other samples consisted of a few pounds of rock that were obtained by chipping the rock face at intervals of 1 foot for the indicated distance given in table 1. The limits of the sample zones were determined in part by radioactivity measurements and in part by the apparent visible limits of the ore zone. Because of local high background radioactivity, the differences in radioactivity between the ore containing rare-earth minerals and the adjacent relatively barren ore or rock in places were small, and for this reason parts of some samples were taken beyond the limits of the radioactive ore. Some samples are therefore diluted with nonradioactive or or rock.

To illustrate the relations between the amounts of rare-earth elements and radioactivity, uranium, thorium, and iron in samples of coarse-grained radioactive magnetite ore, the available data are

TABLE 1.—*Radiometric and chemical analyses of rock and magnetite ore from near the north end of the 6th and 7th levels in the Scrub Oaks mine, Morris County, N. J.*

[Radiometric analyses by B. A. McCall. Chemical analyses by Harry Levine and Roosevelt Moore]

Sample No.	Type of sample	Sampling distance (feet)	Sample site	Material	Equivalent uranium	Uranium	ThO_2	$(RE)_2O_3$*	Fe_2O_3
HK5-34	Chip	16	Stope, 6th level.	Magnetite ore, coarse-grained.	0.036	0.011	0.11	2.28	27.8
35	Grab		Sublevel, 7th level.	Granite gneiss	.053	.026	.14	.24	19.8
36	do		Sublevel, 6th level.	Magnetite ore, coarse grained.	.028	.010	.08	2.10	36.2
37	do		do	do	.034	.011	.10	2.11	37.9
38	do		do	do	.018	.005	.06	1.55	33.1
39	Chip	8	do	do	.021	.007	.035	1.08	55.5
40	do	14	do	do	.034	.013	.10	2.30	39.1
41	do	6	do	Magnetite ore, coarse-grained; and hornblende granite gneiss.	.001	.001	.003	.09	32.4
42	do	5	do	Magnetite ore, coarse-grained.	.031	.010	.08	2.33	43.7
43	do	6	do	do	.026	.008	.06	1.99	42.7
44	do	16	Stope, 6th level.	Magnetite ore, coarse-grained; and pegmatite.	.007	.002	.02	.53	22.3
Average					.027	.009	.071	1.51	35.5

*$(RE)_2O_3$ combined rare-earth oxides including yttrium.

plotted on scatter diagrams (figs. 2–5). Only the last two digits of the sample numbers are used in the scatter diagrams.

The radioactivity (equivalent uranium), uranium, and thorium content of the ore increase directly with an increase in rare-earth content as shown in figures 4, 5, and 6. Sample 35 is radioactive granite gneiss rather than ore.

The rare-earth minerals are most abundant in coarse-grained magnetite ore. The relationship of rare-earth elements to total iron is shown in figure 5. Sample 39 contains a higher percentage of iron than the other samples; it represents a sample interval that includes coarse-grained ore that contains rare earths and some which is barren of rare earths. Sample 41 represents a sample interval that includes very little rare-earth ore. Sample 44 was taken across an interval of ore containing rare earths with intermixed leaner pegmatite [2] which diluted the sample with respect to iron and rare earths. The relatively undiluted ore samples contain 1.6 to 2.33 percent combined rare-earth oxides and about 20 to 30 percent iron.

SEPARATION AND ANALYSIS OF A RADIOACTIVE CONCENTRATE

A sample of radioactive magnetite ore was crushed, sized, and separated magnetically with a hand magnet. Concentration of the radioactive minerals was unsatisfactory at plus 20 to minus 8 mesh grain size, so the material was ground to minus 20 mesh size, then separated magnetically and gravimetrically using methylene iodine, which has a specific gravity of about 3.3 The nonmagnetic heavy-mineral fraction was then separated using a magnetic separator. At settings of 0.2 amperes, a tilt of 14° and a slope of 20°, most of the hematite was separated as a magnetic fraction and most of the radioactive mineral fragments remained in the nonmagnetic fraction.

The radioactive nonmagnetic concentrate contains [3] 0.49 percent equivalent uranium, 0.20 percent uranium, 1.36 percent thorium oxide ($TH0_2$), and 33.36 percent rare-earth oxides including yttrium oxide (Y_20_3). The quantity of each rare-earth mineral in the concentrate has not been determined. The ratios of about 1 part uranium to 6 parts thorium and 1 part thorium oxide to 20 parts combined rare-earth oxides in the concentrate are near to the ratios of these elements in the arithmetic average of 11 samples of ore and rock representing the deposit (table 2).

The results of the analyses of this sample indicate that the uranium, thorium, and combined rare-earth content of a concentrate of the rare-earth minerals can be estimated on the basis of radioactivity measure-

[2] Individual bodies of pegmatite in the rare-earth magnitite ore are too small to be shown on map.

[3] Analysts: B. A. McCall, equivalent uranium; Carmen Johnson, uranium; and Harry Levine, thorium and rare earths.

ments, and that the abundance of these elements in ore can be estimated on faces of ore in the mine.

SPECTROGRAPHIC ANALYSES

Semiquantitative spectrographic analyses of samples of magnetite ore containing rare earths and radioactive rock shown in table 2 indicate that the abundance of rare-earth elements is relatively consistent in similar types of rock taken from different places in the stope and sublevel on the 6th level of the mine.

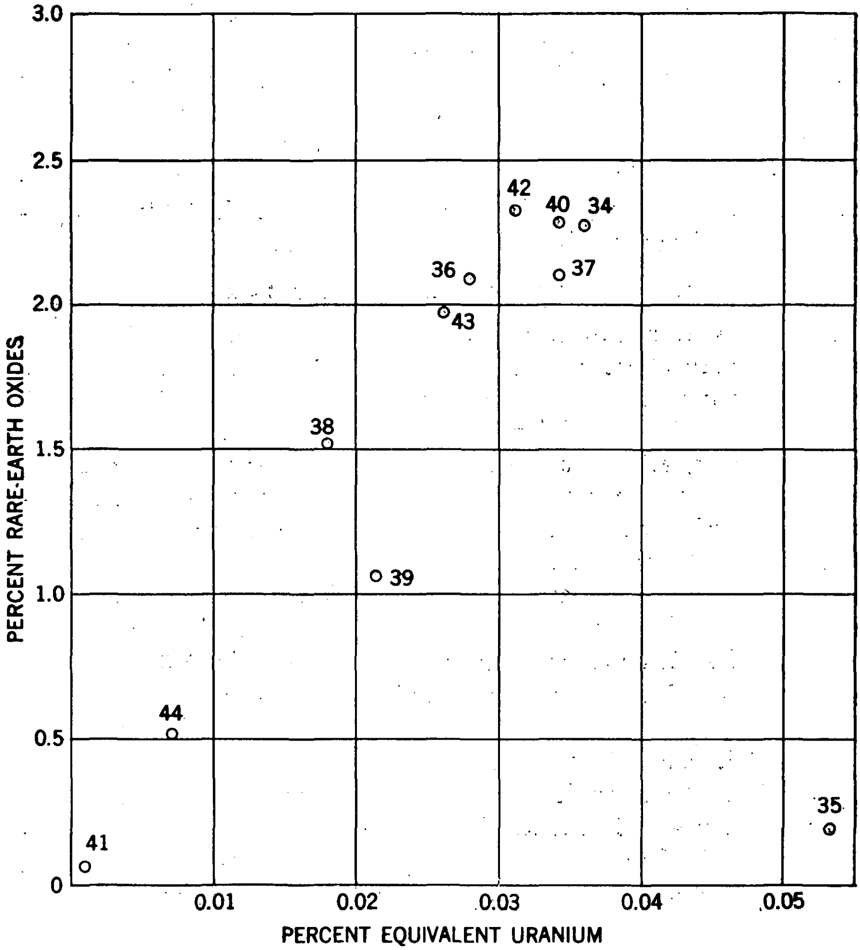

FIGURE 2.—Scatter diagram showing relations between rare-earth oxide content and equivalent uranium of samples of ore and rock from the Scrub Oaks mine, Morris County, N. J.

Quantitative spectrographic analyses of the chemically separated rare-earth fractions of the samples are given in table 3. The abundance of yttrium with respect to cerium is notable. Terbium, holmium, and thulium were not reported in the quantitative analyses, but holmium was detected in the semiquantitative analyses.

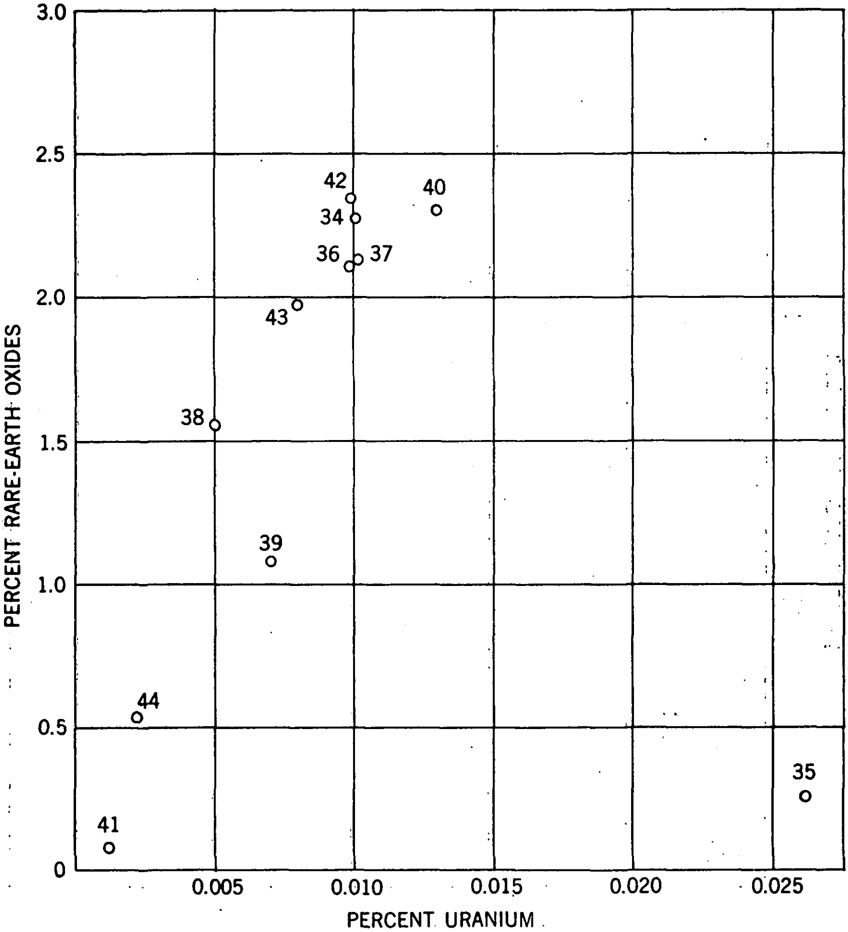

FIGURE 3.—Scatter diagram showing relations between rare-earth oxide content and uranium in samples of ore and rock from the Scrub Oaks mine, Morris County, N. J.

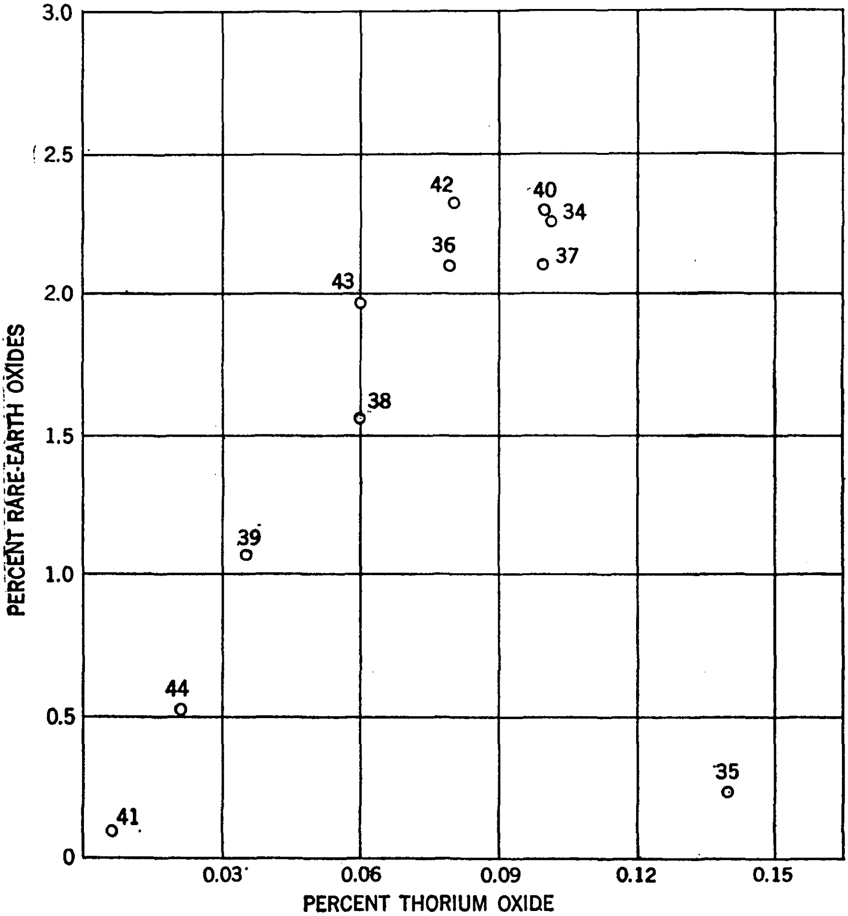

FIGURE 4.—Scatter diagram showing relations between rare-earth oxide content and thorium oxide in samples of ore and rock from the Scrub Oaks mine, Morris County, N. J.

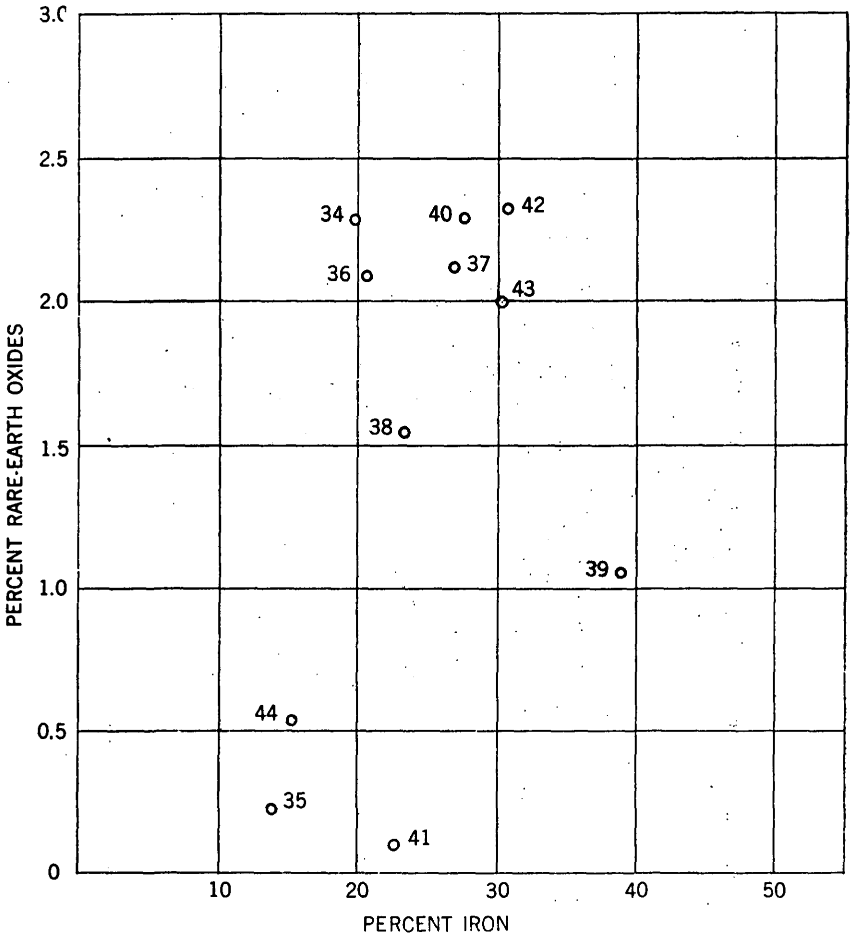

FIGURE 5.—Scatter diagram showing relations between rare-earth oxide content and iron in samples of ore and rock from the Scrub Oaks mine, Morris County, N. J.

TABLE 2.—*Semiquantitative spectrographic analyses, in percent, of radioactive magnetite ore and rock, Scrub Oaks mine, Morris County, N. J.*

[Analyst, K. E. Valentine]

Sample No.	>10	5–10	1–5	0.5–1	0.1–0.5	0.05–0.1	0.01–0.05	0.005–0.01	0.001–0.005	0.0005–0.001	<0.0005
HK5-34	Si, Fe	Al	Na, Ti		Y, Ca, Ce, La, Zr, Mg.	Nd, Pr, Dy, Ba, Th.	Er, Cu, Yb, Gd, Lu, B, Sr.	Sm, Mn, Ho, Ni, V, Ga.	Sc, Pb, Nb	Cr	Be.
35	Si, Fe	Al	Na		Zn, Y, Ca	Th, Mg, Ba, Ti	Cu, Yb, Sr, Dy, Er, Ga, B.	Lu, Mn, V, Nb, Gd, Ni.	Ho, Pb	Cr	Be.
36	Si, Fe	Al	Na	Ti	Y, Ca, Ce, La	Nd, Mg, Ba, Zr, Th.	Dy, Er, Pr, Cu, Sr, B, Gd, Yb, Lu, Ga, Mn.	Sm, V, Ni, Ho	Sc, Pb	Cr	Be.
37	Si, Fe		Ti	Al	Na, Ce, Y, Ca, Nd.	La, Mg, Th	Cu, Dy, Pr, Yb, Zr, Er, Gd, B.	Lu, Mn, Ni, Sm, V, Sr, Ho, Ba.	Ga, Nb, Sc, Pb	Cr	Be.
38	Si, Fe		Al, Na, Ti		Ca, Nd, Y, Ce	Zr, Mg, La	Cu, Dy, B, Pr, Er, Yb, Gd.	Lu, Sm, V, Mn, Sr, Ni, Ho, Ba.	Ga, Nb, Sc, Pb	Cr	Be.
39	Si, Fe		Al, Na	Ti	Mg, Ce, Y, Nd, Ca.	La, Zr	Cu, B, Lu, Pr, Dy, Er, Gd, Yb.	Ba, Mn, Sm, V, Sr, Ho, Ni.	Ga, Pb	Sc, Cr	Be.
40	Si, Fe		Al, Ti	Na	Ca, Ce, Y, Nd	La, Mg, Zr	Cu, Dy, Pr, Er, B, Gd, Yb.	Lu, Mn, Sm, V, Ho, Ni.	Sr, Ga, Ba, Sc, Pb.	Cr	Be.
41	Si, Fe	Al	Na	Ti	Ca, Mg	Cu	Zr, Y, B, V	Mn, Sr, Ba, Ni	Yb, Ga, Pb	Cr	Be.
42	Si, Fe		Ti		Na, Al, Ca, Ce, Y, Nd.	La, Mg, Th, Cu	Zr, Dy, Mn, Yb, Er, Pr, Gd, B.	Lu, Sm, V, Ho, Ni.	Nb, Ga, Ba, Sr, Sc, Pb.	Cr	Be.
43	Si, Fe		Al, Ti		Ca, Nd, Na, Y, Ce.	La, Mg	Cu, Zr, Dy, Pr, Er, Yb, B, Gd.	Lu, Mn, Sm, V, Ho, Ni.	Sr, Ba, Ga, Pb, Sc, Nb.	Cr	Be.
44	Si, Fe	Al	Na	Ti	Ca, Y, Mg	Ce, Nd, Ba, Cu	La, Zr, Sr, Dy, Yb, Pr, B.	Er, Gd, Mn, Ga, Sm, V, Lu, Ni.	Ho, Sc, Pb	Cr	Be.

TABLE 3.—*Quantitative spectrographic analyses of chemically separated total rare-earth fraction of radioactive magnetite ore (reported as percent of ore) from the Scrub Oaks mine, Morris County, N. J.*

[Analysts, Claude Waring and Helen Worthing]

Sample No.	Y	La	Ce	Pr	Nd	Sm*	Eu*	Gd	Dy	Er*	Yb*	Lu*
HK5-34	0.16	0.55	0.73	0.04	0.26	0.007	*0.00A	0.026	0.043	*0.00B	0.000A	0.00B
35	.16	N. D.	.01	N. D.	N. D.	.007	N. D.	.006	.009	.00B	.017	N. D.
36	.63	.17	.56	.04	.09	.007	.00A	.035	.026	.0A	.035	.0A
37	.16	.56	.64	.05	.26	.007	.00A	.035	.043	.00B	.000A	.00B
38	.43	.08	.38	.04	.21	.008	.0A	.017	.009	.0A	.00B	.00A
39	.12	.28	.32	.03	.13	.007	.00A	.017	.026	.00B	.000A	.00B
40	.16	.60	.78	.05	.21	.005	.00A	.035	.043	.00B	.000A	.00B
41	.02	.003	.04	N. D.	.005	N. D.	N. D.	N. D.	N. D.	.00A	.000B	.00A
42	.79	.09	.68	.04	.17	.00A	.00A	.035	.026	.0A	.026	00A
43	.63	.09	.70	.03	.09	.00A	.00A	.017	.017	.00B	.026	.00B
44	.08	.13	.13	.03	.02	.00A	.00A	.009	.009	.00B	.000A	.00B

*Er, Eu, Yb, and Sm (in part), and Lu are semiquantitative estimates.

A, 1-5; B, 5-10; N. D., not detected.
Looked for but not found: Tb, Ho, Tm (Ho was detected in semiquantitative analyses).

PETROLOGY

The rare-earth rocks in the Scrub Oaks mine are distinctly coarser grained than the country rock and the typical magnetite ore; and they have sharp contacts with the granitic wall rocks.

Magnetite ore containing rare earths consists mainly of magnetite, hematite, and quartz, and some reddish opalescent albite-oligoclase, perthite, antiperthite (Sims' microperthite and microantiperthite) and microline. The albite-oligoclase has partly replaced the other feldspars. Rare-earth minerals in dull brick-red aggregates of xenotime and doverite and gray bastnaesite and chevkinite constitute about 3 percent of the rocks. Microbreccias, partly healed by calcite veins that contain sulfides, are present throughout the rock. Calcite and rare-earth fluocarbonates constitute 2 to 5 percent of the rock.

The rare-earth part of the pegmatite consists mainly of antiperthite, perthite, microline, and quartz, and lesser amounts of magnetite and rare-earth minerals, hornblende, and biotite. Albite-oligoclase occurs as a replacement of antiperthite and perthite. The rock is spotted with aggregates of the gray and red rare-earth minerals.

The microantiperthite granite wall rocks have been altered near the contacts with the rare-earth rock. Locally much epidote, albite-oligoclase with peculiar checkerboard twin pattern, calcite, and uralite have replaced the antiperthite and microline, suggesting an increase in sodium and calcium at the expense of potassium. The amphibole and biotite have been altered to chlorite, which is clouded with fine-grained inclusions of magnetite and hematite. Chlorite-rich masses are particularly abundant at the contact between the rare-earth deposit and its wall rocks.

MINERALOGY

The rare-earth deposit consists of about 30 minerals, including the silicates and the iron and titanium oxides and sulfides. Most of the known minerals in the deposit are typical of the magnetite ore deposits, pegmatites, and late sulfide-carbonate veins of the Dover district. Potassium feldspar, plagioclase, quartz, and other silica-rich minerals are abundant, as well as magnetite and hematite. The minerals containing rare earths are doverite, bastnaesite, xenotime, chevkinite, zircon, sphene, apatite, and monazite. Some rare-earth minerals or aggregates in the deposit have not yet been identified. Other minerals that are minor constituents of the rocks are anatase, augite, biotite, bornite, chalcopyrite, chlorite, epidote, garnet, hornblende, ilmenite, pumpellyite(?), pyrite, rutile, spinel, sericite, and tremolite. The most distinctive feature of the deposit is the abundance of rare-earth fluocarbonates and calcite. Minerals such as nepheline, sodalite, and soda pyroxenes that are common in other rare-earth deposits are absent.

OPAQUE MINERALS

Magnetite.—Magnetite, the most abundant of the opaque minerals, occurs largely as black, coarse, anhedral and rounded grains, as veinlets, as rims around silicates, and as aggregates of coarse and medium grains. Some fine euhedral or subhedral crystals and isolated grains of magnetite are enclosed in coarse-grained masses of quartz, albite-oligoclase, or antiperthite, in both the magnetite and pegmatite parts of the deposit. In addition, a little very fine grained magnetite and probably some hematite form dustlike clouds in chlorite, in rare-earth minerals, and in late sulfide-carbonate veins. Much of the magnetite apparently is homogeneous, but some grains are replaced, veined, and embayed by hematite and others contain abundant ilmenite in fairly coarse exsolution bands that are elongate and parallel. Minute lathlike inclusions within the magnetite and the ilmenite bands are possibly rutile and spinel.

The magnetite of the rare-earth deposit is notably coarser grained than most of the magnetite in the main Scrub Oaks iron ore and in the adjacent wall rocks; but similar coarse-grained magnetite ore not known to contain rare earths is present locally in the Scrub Oaks iron ore body.

Hematite.—Hematite is common as coarse irregular grains with blue-black metallic luster interspersed with magnetite grains, and as irregular embayments in magnetite. Locally, spindle-shaped hematite is interbanded with brown vitreous sphene, and elsewhere with white, cloudy leucoxene (?). In places, hematite apparently is more abundant near the rare-earth mineral clusters than in the rock away from them. Some of the opaque dustlike inclusions in red doverite aggregates are nonmagnetic and have been identified as hematite (Smith and others, 1955, p. 31). Very thin bright-red opaque films coating surfaces of fractures in quartz, magnetite, and other minerals are nonradioactive and may be hematite.

Ilmenite.—Ilmenite occurs in small lath-shaped exsolution intergrowths in parallel alinement in magnetite. In places, the narrow elongate bodies lie parallel to a brown nonopaque mineral with similar habit, possibly rutile, and also apparently replace it. Some ilmenite laths meet at acute angles, with the brown nonopaque mineral between them. Minute inclusions of a lustrous light-gray nonopaque mineral in both ilmenite and the brown nonopaque mineral are oriented parallel to the long axes of the ilmenite laths.

Pyrite.—Pyrite is widely dispersed as a minor constituent in the rare-earth deposit and adjacent wall rock. It is fine grained, replaces other minerals, and is closely associated with calcite. The pyrite occurs in late veins of calcite, quartz, chlorite, magnetite, and hematite, 1 to 2 millimeters thick that cut across older quartz, magnetite, bastnaesite, and doverite aggregates. The pyrite is in minute subhedral to euhedral grains in the margins of the calcite veinlets, and it is interspersed locally in the wall rock near the veinlets. In one specimen small late-stage pyrite crystals are alined in a fracture that crosses a calcite veinlet, and pyrite forms dustlike inclusions in bastnaesite and red doverite aggregates.

Chalcopyrite.—Chalcopyrite is associated with pyrite, and also forms thin intergranular films on magnetite. If most of the copper in the samples analyzed spectrographically is in chalcopyrite, much of the sulfide that resembles tarnished pyrite probably is chalcopyrite.

Bornite.—Bornite was noted by W. L. Smith (written communication, 1956) in polished sections of magnetite ore containing rare earths.

Leucoxene.—Leucoxene, a cloudy amorphous titanium dioxide alteration product of other titanium minerals, is intimately associated with bastnaesite as cloudy gray or white isotropic masses.

NONOPAQUE ROCK MINERALS

Quartz.—Quartz is the most abundant of the nonopaque minerals, and is particularly abundant in the rare-earth magnetite rock. Most of the quartz is in coarse-grained, clear, anhedral masses, but some very coarse-grained quartz is bluish or smoky. Small euhedral grains of clear quartz with hexagonal outlines are commonly imbedded in magnetite, hematite, doverite aggregates, and bastnaesite, and veinlets of quartz cut across nearly all of the known minerals except calcite and the sulfides. The quartz associated with late pyrite-calcite veins is very fine grained, milky and cloudy, and it resembles jasperoid. One specimen of very clear quartz contained minute hairlike crystals, probably rutile.

Albite-oligoclase.—The main feldspar in the rare-earth magnetite deposit is a pink to red coarse-grained anhedral, albite-oligoclase (variety aventurine), and fresh specimens have the marked copper-colored reflections of sunstone. Albite-oligoclase has almost completely replaced the antiperthite and microcline of the original pegmatite, and it also may have been a minor primary constituent of the pegmatite, occurring in small discrete grains. Many stages of overgrowth and replacement of the potash feldspar by plagioclase were observed. Albite-oligoclase has been replaced locally by most of the younger minerals, especially biotite, quartz, magnetite, doverite, bastnaesite, calcite, and sericite.

Orthoclase.—Large anhedral grains of untwinned orthoclase are common in the pegmatite part of the rare-earth deposit. The orthoclase is closely associated with antiperthite and checkerboard plagioclase, which appears to have replaced it. Much of the orthoclase has been altered or partly replaced by dark silicates, magnetite, or calcite.

Perthite and antiperthite.—The wall rocks of the rare-earth deposit, and of the pegmatite containing rare earths at the northeast end of the deposit, contain much antiperthite. Much of it seems to be the usual albite-orthoclase intergrowth containing more albite than orthoclase. A small proportion of the grains are 50 percent or more potash feldspar and thus are perthite rather than antiperthite.

Microcline.—Coarse grains of microcline showing spindle-shaped twin lamellae were noted in one thin section of the rare-earth, magnetite ore.

Hornblende.—Green or greenish-brown grains of hornblende form a common accessory mineral in the pegmatite and a less common accessory mineral in the rare-earth magnetite rock. The hornblende is altered to chlorite, is rimmed by sphene and biotite, and in turn rims zircon crystals. The oldest magnetite is deposited in clusters in or near the hornblende and augite in the rare-earth deposit.

Augite.—Minor amounts of coarse-grained anhedral or subhedral augite rimmed by biotite and sphene are in the pegmatite. The grains are pale greenish brown, with marked, nearly right angle cleavage planes. The relief is high, the birefringence is rather strong, and the mineral is optically positive. Augite has been replaced by magnetite, biotite, chlorite, and the rare-earth minerals, and very little of it remains in the rare-earth-bearing magnetite rock.

Biotite.—Large greenish or yellow-brown anhedral to subhedral grains of biotite are common in the pegmatite that contains rare earths. The biotite has replaced feldspars and rims hornblende and other silicates, and in turn has been replaced by chlorite.

Fine-grained biotite rimmed by and closely associated with chlorite occurs in magnetite rock containing rare earths. This biotite is probably younger than the larger grains described previously.

Chlorite.—Green chlorite, a widespread minor constituent in the rare-earth deposit, occurs as an alteration product of biotite, hornblende, and augite, and it is particularly abundant at the contacts of the rare-earth deposit. Chlorite also forms minute green flakes along the walls of some of the late calcite-quartz-sulfide veinlets.

Muscovite (sericite).—Fine-grained muscovite or sericite occurs as flaky aggregates in the contact zone between magnetite and feldspar and is closely associated with the late veins of magnetite.

Anatase.—Anatase, a fine-grained, gray vitreous mineral, is locally abundant in the rare-earth magnetite ore in large, uniformly fine grained crystalline masses that are interstitial to the magnetite grains and that are clustered near and in places rim the doverite grains. The mineral is most abundant in the richest parts of the rare-earth deposit, where it comprises 1 to 5 percent of the rock. Bastnaesite replaces anatase locally.

Rutile.—Small blood-red to red-brown subhedral grains of rutile are closely associated with the rare-earth minerals and in minute cracks near the deposit it is associated with red hematite. In one specimen microscopic hairlike crystals, probably rutile, are included in colorless quartz.

Calcite.—Calcite is a common minor constituent of the rare-earth deposit. It is the principal mineral of the later sulfide-bearing veins and forms abundant fine-granular aggregates that replace the rare-earth minerals, chlorite, and feldspars.

Pumpellyite (?).—A dark green to black fibrous mineral between grains of hematite and magnetite and in fractures in magnetite was noted in a few polished sections of rare-earth-bearing magnetite ore. This minor accessory mineral may be pumpellyite, a hydrous calcium aluminum silicate. Sims (1953, p. 280) states that pumpellyite is present in the magnetite ore and in the wall rocks of the Scrub Oaks deposit.

Garnet.—Small isotropic crystals of colorless garnet with dodecahedral faces were noted in a doverite aggregate. The crystals are embayed by doverite and other associated minerals.

Spinel.—Small euhedral isotropic grains of colorless spinel embedded in magnetite and associated with sphene were noted in one specimen.

NONOPAQUE RARE-EARTH MINERALS

Doverite aggregates.—Doverite, a new species of yttrium fluocarbonate (Smith and others, 1955, p. 31) but possibly an yttrium analogue of synchisite, occurs in brick-red aggregates that resemble red jasper and which are intimate mixtures of doverite, xenotime, hematite, and quartz. The aggregates commonly are 1 to 10 millimeters long, but a few are as much as 3 centimeters. Many of the masses are irregular in outline, and some are roughly tabular. A few have moderately well defined crystal outlines that are combinations of prisms with pyramids or domes; such masses may be pseudomorphous after a mineral that they have replaced. The red aggregates are fairly uniformly distributed in the ore, but locally, particularly where abundant, they appear to be concentrated in layers as clusters of small tabular masses. Red aggregates constitute about 3 percent of some samples of ore. Many of the red aggregates enclose euhedral crystals of quartz, magnetite, or zircon, or partly replaced feldspar or garnet. Magnetite, quartz, bastnaesite, anatase, and probably chevkinite form rims around some doverite aggregates or partly replace them. The bastnaesite rims are white, buff, or gray and locally exhibit wavy microbanded textures.

A pale yellow translucent microgranular mineral, with a birefringence similar to that of calcite, observed in a thin section of a brick-red aggregate is probably doverite. It is thoroughly but irregularly intermixed with deep yellowish-brown grains of high relief and birefringence (probably xenotime) and clouded and less translucent red material. The red material may also be doverite. Some aggregates also contain lustrous opaque hematite and colorless quartz in fine-grained irregular masses. The abundance of the minerals in the aggregates has not been determined.

A chemical analysis of the doverite aggregates follows (Smith and others, 1955, p. 31):

	Percent
$(R.E.)_2O_3$*	44.36
ThO_2	1.62
SiO_2	9.70
Fe_2O_3	8.90
CaO	9.80
P_2O_5	8.75
Al_2O_3	.54
UO_3	.22
TiO_2	.75
MgO	.53
H_2O total	1.35
CO_2	11.75
F	2.87
Total	101.14
Less O=F	1.21
Total	99.93

*Combined rare-earth oxides including 7.4 percent Ce_2O_3.

Spectrographic analysis shows Y as a major component, minor amounts of Ca, La, Gd, and traces of Dy, Er, Yb, Nd, Pr, Lu, Ho, Tm, and Eu.

Locally where the late veins cut bastnaesite, a red mineral resembling doverite along the walls of the veins, possibly indicates a late generation of doverite which was deposited from carbonate solutions.

Xenotime.—Xenotime, an yttrium phosphate, occurs in the doverite aggregates as minute clear deep yellowish-brown grains of high birefringence and relief. Similar small yellowish-brown anhedral grains are scattered through bastnaesite. Smith and others (1955, p. 31) found that a residue of quartz and xenotime was left when hematite and doverite were leached from the aggregates. Minute grains of a yellow mineral that may be xenotime also occur in a magnetite-bearing albite-oligoclase-antiperthite granite gneiss from the 7th level of the mine. The grains have rectangular or rounded outlines.

Bastnaesite.—Bastnaesite, a cerium fluocarbonate, occurs abundantly as thin buff-colored or white rims around doverite aggregates and gray rims around chevkinite; as small irregular, colloidal or microcrystalline masses embaying doverite aggregates; and separately, as disseminated buff-colored irregular masses and roughly rectangular or cubic gray masses in the rock. The bastnaesite is in thin films a fraction of a millimeter thick, in masses a few millimeters across, and in equant to elongate rectangular masses as much as a centimeter long.

Bastnaesite, although always very fine grained, varies widely in color and texture. White, pink, pale-gray, buff, reddish-brown, waxy dark-gray, and chocolate-brown bastnaesite were noted under the microscope, and many of these varieties were checked by X-ray diffraction analyses. The dark-colored bastnaesite is impure and intimately mixed with other minerals as xenotime, hematite, chevkinite, doverite, and leucoxene, whereas the nearly white masses mainly appear to be pure microaggregates of tabular bastnaesite crystals. Much of the light-colored bastnaesite, however, is intermixed with leucoxene. X-ray diffraction analysis of one bastnaesite sample showed bastnaesite with synchisite or doverite. The difference in the color of bastnaesite may partly result from differences in composition, for some of the buff bastnaesite replaces doverite and xenotime, and thus may contain much yttrium. The lightest colored bastnaesite appears to have been deposited as fillings and did not replace older rare-earth minerals. A spectrographic analysis of a specimen of bastnaesite is reported in table 4. The high titanium content of the bastnaesite as shown in the spectrographic analysis may be due to impurities within the mineral structure or to intermixed minerals.

Some of the bastnaesite is microgranular and uniform, but a large part is strongly banded, with minute white, buff, gray, and reddish streaks. Some bastnaesite has typical colloform textures; it is in spheroidal masses that have a net of minute radial shrinkage cracks. Generally the older bastnaesite is finer grained than the younger varieties, and much of it is too fine to be distinguished except under high magnification.

The younger bastnaesite is commonly white and coarsely microcrystalline and platy. Some of it occurs at the junctions of an intersecting network of obscure, thin, healed fractures, and some of the more coarsely crystalline white bastnaesite fills minute vugs in colored bastnaesite and in the thin fractures. Calcite, pyrite, and magnetite

TABLE 4.—*Spectrographic analyses, in percent, of minerals containing rare earths from the Scrub Oaks mine, Morris County, N. J.*

[Analyst, K. E. Valentine]

Mineral	>10	5–10	1–5	0.5–1	0.1–0.5	0.05–0.1
Apatite	Ca, P		Y, Ce, Si, La	Nd, Th	Yb, Er, Al, Gd, Pr, Dy, Fe.	Mg, Na, B, Sr, Pb.
Bastnaesite	Ce, Ti	La	Y, Ca, Th, Nd, Pr, Si.	Fe	Al, Gd, Dy, Er, Mg, Yb.	
Chevkinite	Ce, Ti	Fe, Si	La, Y, Th, Mg, Nd, Ca.	Gd, Al, Pr	Zr, Mn, Yb, Ba.	
Sphene	Si	Ca, Fe, Ti	Ce, Y	Al, Nd, La	Dy, Gd, Er, Yb, Mg.	Sm, Nb, Pr.
Zircon	Si, Zr		Fe	Hf	Ca, P, Al, Y	Mg, Ti, Ce.

Mineral	0.01–0.05	0.005–0.01	0.001–0.005	0.0005–0.001	0.0001–0.0005
Apatite	Lu, Mn, Eu, Ho, Ti, V.	Sm, Sc	Ba, Cr	Be	
Bastnaesite					
Chevkinite					
Sphene	Ba, Zr, Lu, Sr, Mn.	Eu	Sc	Cu, Cr	
Zircon	Mn, B, La, Yb	Ni, Lu, Pb	Co, Ba		Be.

veinlets transect some of the bastnaesite, and coarse-grained magnetite and a reddish rare-earth apatite rim and locally replace it.

Chevkinite.—Chevkinite, a titano-silicate of the cerium-earth metals, is fairly common in the rare-earth magnetite ore, but because of its dark color it is not readily recognized. It may be more abundant in the coarse-grained ore than has yet been noted. Doverite is rimmed by chevkinite, or minerals of similar appearance; and chevkinite, in turn, is rimmed and replaced by bastnaesite and leucoxene.

Chevkinite has been identified by D. D. Riska of the U. S. Geological Survey in X-ray diffraction studies of a brownish-black mineral from samples of the ore. The mineral tentatively identified in thin section and hand specimen as chevkinite forms lustrous dark-brown cubes with irregular margins. It is translucent and orange brown on thin edges, has a hardness of 5.5 to 6, and has an index of refraction ranging from 1.93 to 1.95, as determined by Howard W. Jaffe, U. S. Geological Survey. The mineral is isotropic and partly metamict for it gives no X-ray pattern until heated; after heating some of the X-ray lines are weak. A few specimens after heating in air gave an X-ray pattern of cerium oxide, but others after heating in an inert atmosphere give a clear chevkinite pattern. Chevkinite has been altered or replaced in varying degrees by gray bastnaesite. Samples of material resembling chevkinite, but more waxy gray in appearance, gave bastnaesite X-ray figures. An analysis of a specimen of chevkinite is given in table 4.

Apatite.—Radioactive red apatite, rich in yttrium and cerium earths, is a fairly common mineral in the rare-earth deposit, where it replaces and forms rims on chevkinite and bastnaesite. The apatite contains as much as 10 percent rare earths. A spectographic analysis is given in table 4.

Coarse-grained red and reddish-brown masses of similar radioactive rare-earth apatite were noted in a few specimens of pegmatite containing zircon on the dump of the Richard mine 2½ miles northeast of the Scrub Oaks mine. For a description of the Richard mine, see Sims (1953, p. 295–298). A spectrographic analysis shows that the apatite is rich in cerium, yttrium, and lanthanum and is similar in the quantities and proportions of other rare earths that it contains to apatite from the Scrub Oaks mine. Apatite without notable radioactivity is abundant at the Canfield phosphate deposit about a mile south of the Scrub Oaks mine.

Zircon.—Zircon is common in the coarse-grained rare-earth magnetite ore as dark-brown to maroon euhedral pyramidal crystals ranging in cross section from 1 by 0.5 millimeter to about 1 centimeter by 5 millimeters. In some parts of the magnetite ore zircon constitutes a few percent of the rock, but generally it is less abundant. Most of the crystals are clear and unaltered but some of the coarser grained ones have pale-gray or tan zones near their centers. These zones, in one or two crystals at least, surround a core of a grayish rare-earth mineral (possibly bastnaesite or altered chevkinite). Most zircons have smooth, lustrous crystal faces, combinations of prisms and pyramids, but a few zircons have rounded, vicinal faces in part and appear to have intergrown with bastnaesite or magnetite. Many zircons are twisted and fractured, and these fractures are filled with bastnaesite, quartz, calcite, and chlorite; a few zircons are rimmed by bastnaesite, doverite, and magnetite.

An analysis (table 4) of some of the clear, unaltered zircons shows that they contain rare earths.

Sphene.—Brownish sphene in coarse anhedral and subhedral grains is common and locally abundant in the rare-earth deposit, particularly in the rare-earth magnetite rock. In some specimens sphene constitutes as much as 10 percent of the rock. The sphene ranges in color from yellow to brown and is in translucent grains. It rarely shows crystal boundaries and exhibits a single direction of parting. The composition of a specimen of sphene is given in table 4.

Sphene rims and embays magnetite and doverite and in turn is rimmed by bastnaesite and leucoxene.

Monazite.—Minute, irregular particles of a red vitreous mineral in a specimen of radioactive coarse-grained rock from the 7th level of the mine have been identified by X-ray diffraction analysis as monazite.

PARAGENESIS

The sequence of deposition of minerals in the rare-earth deposit is complex (fig. 6), as interpreted from the spatial relationship of the minerals. It includes simultaneous deposition, replacement, and alteration of mineral species, and at least two periods of shattering. The periods of shattering separate the principal stages of mineral deposition. The deposit was formed by: (1) deposition of the pegmatite minerals, notably feldspars and other silicates, quartz, and possibly some accessory magnetite; (2) minor shattering in the pegmatite; (3) deposition of magnetite, hematite, quartz, and rare-earth minerals in the shattered pegmatite; (4) minor shattering in the magnetite-rich rock; (5) deposition of calcite and sulfides in fractures in the magnetite rock.

The pegmatite in the rare-earth deposit, except for its rare-earth mineral content, is similar to others in the Dover district. Sims (1953, p. 263) believes that they are genetically related to the hornblende granite, alaskite, and albite-oligoclase granite. Zircon-rich pegmatites are known in other parts of the highlands: near Mount Olive, N. J., and south of Allentown, Pa.

The ore zones in the Scrub Oaks magnetite deposit are generally parallel to the foliation of the wall rocks, but in detail have irregular outlines, with sharp, crosscutting contacts. Sims (1953, p. 285–286) believes that the magnetite in the Dover district was emplaced after the pegmatites and cites evidence that magnetite replaced minerals of the pegmatites. Although the coarse-grained magnetite ore containing abundant rare-earth minerals is apparently not typical of the Scrub Oaks ore body, the relationship of the coarse-grained ore to the pegmatites is the same as that noted by Sims for magnetite ore bodies in the district. The solutions that deposited the iron and rare-earth minerals apparently contained fluorine, carbon dioxide, and phosphorus, for rare-earth fluocarbonates and rare-earth phosphates are abundant in the coarse-grained ore. The iron- and rare-earth minerals replaced selectively the brecciated parts of the pegmatite. The rare-earth minerals, some colorless quartz, and albite-oligoclase feldspar were deposited mainly during the early and middle periods of deposition of magnetite and hematite. The authors believe that the coarse-grained rare-earth magnetite ore may be a local variant of ore deposited from the same fluids that produced the finer grained magnetite ore of the Scrub Oaks deposit. Differentiation of the rare-earth elements during deposition is indicated by the mineral relationships. Deposition of apatite and zircon appears to have begun

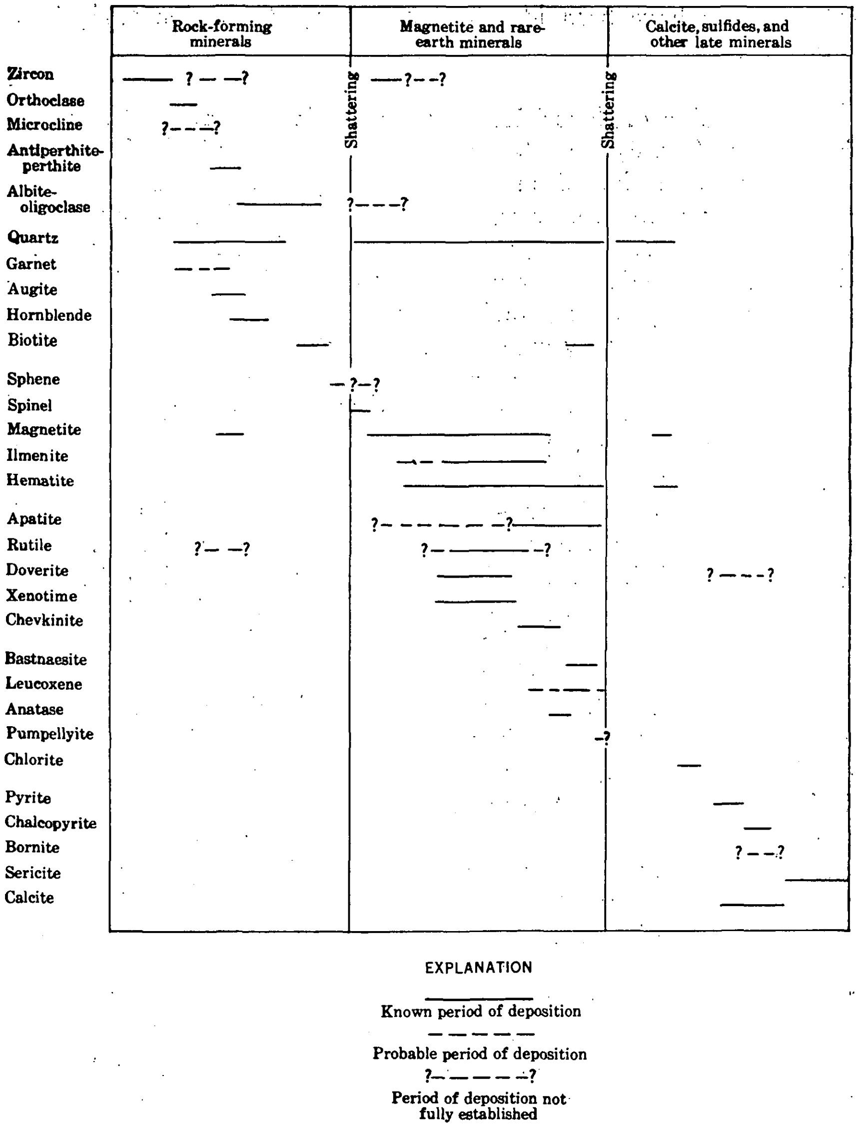

FIGURE 6.—Sequence of deposition of minerals in the Scrub Oaks rare-earth deposit.

early in the formation of the rare-earth deposit. Both the cerium and yttrium groups of rare-earth elements are abundant in these minerals (table 1). The yttrium-rich minerals xenotime and doverite were deposited during the middle of the period of emplacement of the ore minerals, then cerium-group minerals, chevkinite, bastnaesite, and sphene were deposited. Coarse-grained anhedral masses of apatite replace earlier formed rare-earth minerals, and veinlets of apatite cross these minerals. Some magnetite-hematite grains are cut or rimmed by rare-earth minerals, others are intricately intergrown with these minerals. Magnetite also rims rare-earth minerals. These relationships suggest that magnetite deposition began before the formation of the rare-earth minerals and ended after these minerals had been deposited.

The rare-earth deposit in the Scrub Oaks mine is similar in some respects to the rare-earth-bearing magnetite ore body at Mineville, Essex County, N. Y. (McKeown and Klemic, 1956). At each of these localities the rare-earth elements are in minerals that were deposited during the emplacement of the iron ore minerals, and the cerium-group and yttrium-group elements are abundant. At the Scrub Oaks deposit, however, differentiation of the rare-earth elements into minerals rich in cerium earths and others rich in yttrium earths has taken place to a greater extent, perhaps because of the availability of fluorine and carbonate solutions. The Scrub Oaks deposit differs from the Mountain Pass, Calif., rare-earth deposits (Olson and others, 1954) in that the former occurs in granitic rather than alkalic rocks, and it contains both yttrium and cerium earths, whereas the Mountain Pass deposits contain relatively little yttrium and much cerium.

The rare-earth rock in the Scrub Oaks deposit was probably derived from the same common source as the nonradioactive magnetite ore of the Scrub Oaks iron deposit. Sims (1953, p. 283–284) states that the magnetite deposits of the Dover district were derived from a granitic magma that consolidated to form hornblende granite and alaskite. He proposes that during the progressive crystallization of the magma, the more mobile and volatile parts of it produced pegmatite, then magnetite bodies. The rare-earth deposit seems to be a variant of the magnetite differentiates.

The calculated ages of three specimens of zircon from the rare-earth deposit in the Scrub Oaks mine are given below.

Analyst	*Method*	*Age of zircon in millions of years*
David Gottfried.	U : Pb, Th : Pb	550
David Gottfried.	Pb : alpha (Larsen method)	545
H. W. Jaffe.	Pb : alpha (Larsen method)	600

David Gottfried estimated that the errors in the age determinations by the Larsen method are probably not more than ± 10 percent.

The ages of these zircon specimens probably represent the age of the rare-earth magnetite ore. If this ore is a variant of the main magnetite deposit, the zircon ages also represent the approximate age of the Scrub Oaks iron ore body.

Veinlets of quartz, sulfides, and calcite cut the rock- and ore-forming minerals and are distinctly younger than the ore body. Sims (1953, p. 278–279) reports that pyrite occurs as veinlets and disseminated grains in the wall rock of some ore bodies in the district, and as local, late veinlets in other deposits. How much younger the pyrite veins are than the magnetite in the Scrub Oaks deposit is not known. Transverse faults described by Sims (1953, p. 299) that offset the main ore body are not reported to be mineralized with sulfides; therefore the fractures and the pyrite veinlets may be older than the major faults.

EVALUATION

The rare-earth deposit in the Scrub Oaks mine appears to be a potential source of cerium- and yttrium-group rare earths, thorium, and uranium as a byproduct of iron. The rare-earth-magnetite ore is distinctive in appearance, can be detected by its abnormal radioactivity, and occurs in a zone that appears to follow the plunge of the main ore body. These features are aids in locating the ore, but the irregularity of the deposit makes it difficult to determine the amount of ore in the deposit. Further exploration will be needed if the approximate tonnage of ore is to be determined.

The rare-earth minerals are amenable to mechanical separation and concentration by a refinement of the methods that are used in extracting iron ore minerals. The problems of mining and milling the ore to produce profitably a marketable concentrate involve factors outside the scope of this study. The amount and tenor of the ore that has been examined suggest that the deposit is worthy of further investigation.

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