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Abundance and distribution of thorium in the carbonatite stock
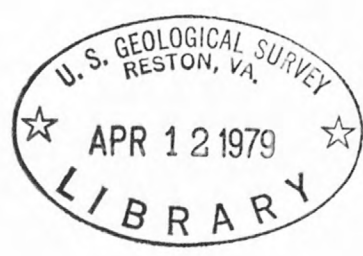at Iron Hill, Powderhorn district, Gunnison County, Colo.

By

Theodore J. Armbrustmacher, 1946-

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ABUNDANCE AND DISTRIBUTION OF THORIUM IN THE

CARBONATITE STOCK AT IRON HILL, POWDERHORN

DISTRICT, GUNNISON COUNTY, COLORADO

by T. J. Armbrustmacher

ABSTRACT

The carbonatite stock at Iron Hill is part of an alkalic complex
of Cambrian or latest Precambrian age containing pyroxenite,
uncompahgrite, ijolite, nepheline syenite, and related rocks
characterized by their subsilicic composition and by their lack of
calcic plagioclase. Thorium averages 36.2 parts per million (ppm) Th
(0.0041 percent ThO_2) in the carbonatite, which also contains
considerably more Ba, Ce, Nd, La, Nb, P, Mn, Mo, Sr, U, and rare-
earth elements than average igneous rocks. Thorium content of the
carbonatite ranges from 6 ppm Th (0.0007 percent ThO_2) 150 ppm Th
(0.017 percent ThO_2), and several areas of anomalous concentration
are apparent. The distribution of thorium is not the same as the
distribution of niobium and rare-earth elements. Thorium abundances
of the level found in the carbonatite at Iron Hill are of little
economic interest unless considered as a byproduct of potential
niobium, rare-earth, and uranium exploitation.

INTRODUCTION

The alkalic rocks and especially the carbonatite stock at Iron
Hill, near Powderhorn, Colorado, have been intensely studied since
1912 (Larsen, 1942) not only because of their unusual lithologies but
also because of the economically significant mineral
concentrations. Economic minerals associated spatially and
genetically with these rocks include vermiculite and minerals that
contain thorium, iron, titanium, niobium, and rare-earth elements.
Several reports by government agencies and mining company
representatives have discussed various aspects of the economic
geology of the complex of alkalic rocks, but the abundance and
distribution of thorium in the carbonatite stock have not been
investigated in detail. The interest in the thorium content of the
stock results mainly from the fact that thorium is a potential
byproduct of possible future niobium and rare earth exploitation.

This study was conducted in order to provide resource data on
one of the principal thorium deposits in the United States (Staatz
and others, 1979) for a Department of Energy contract with the U.S.
Geological Survey.

ACKNOWLEDGMENTS

Robert R. Norman of Buttes Gas and Oil Co. arranged for
permission to investigate the thorium resource potential of their
land holdings at Iron Hill. James V. Thompson of Kaiser Engineers,
consultant to Buttes, visited us in the field and discussed the
geology of the area. Jerry C. Olson of the U.S. Geological Survey
provided unpublished data and also discussed various aspects of the

geology of the area. Semiquantitative spectrographic analyses were performed by L. A. Bradley, and laboratory gamma ray spectrometer analyses were performed by C. M. Bunker and C. A. Bush, all of the U.S. Geological Survey. The cost analyses of mine and mill models were provided by J. F. Lemons, Jr., L. V. Coppa, and B. V. Clingan of the U.S. Bureau of Mines. Mineral separations and other supporting laboratory work were conducted by Isabelle K. Brownfield and William F. Robinson IV. Brownfield also constructed the cross sections across the Iron Hill carbonatite stock and determined the volume of carbonatite used in the resource calculations. Michael B. Sawyer calculated the correlation coefficients used to test the strength of association of various element pairs.

GELOLOGIC SETTING

The carbonatite stock (fig. 1) is part of the complex of alkalic rocks at Iron Hill originally described by Larsen (1942). The complex, which occupies an area of about 30 square kilometers, consists chiefly of pyroxenite, magnetite-ilmenite-perovskite segregations, uncompahgrite, ijolite, hybrid pyroxenite-syenite rocks, nepheline syenite, and carbonatite, listed oldest to youngest (Hedlund and Olson, 1961). Rocks of the complex were emplaced about 570 million years ago (Olson and others, 1977) into Precambrian X Powderhorn Granite and metamorphic rocks, which are locally fenitized adjacent to the complex. Parts of the complex are covered by ash-flow tuffs, welded tuffs, and colluvium mainly of Oligocene age and by colluvium and alluvium of Quaternary age, mainly along the drainages of Cebolla, Deldorado, and Beaver Creeks.
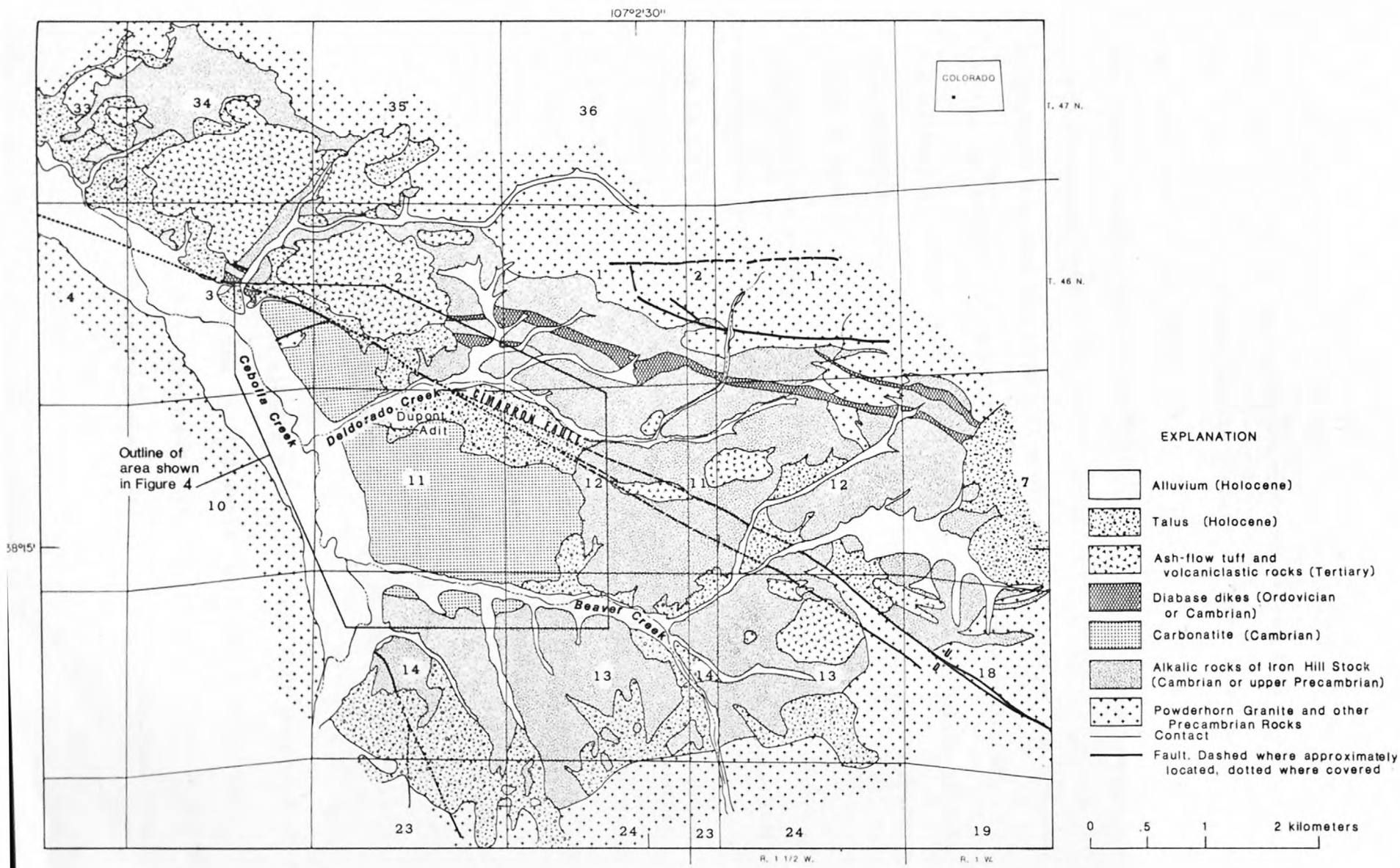
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Figure 1.-Geologic map of the alkalic complex at Iron Hill, Gunnison County, Colorado. Modified from Hedlund and Olson(1975) and Olson (1974).

The complex is bisected by the Cimarron fault. Hedlund and Olson (1975) indicate that relative movement on the fault is such that a deeper level of the alkalic complex is exposed on the northeast side of the fault. The structural interpretation of Temple and Grogan (1965), however, suggests that a deeper level is exposed on the southwest side of the fault. Regardless of the interpretation, nearly all of the uncompahgrite, most of the ijolite, and the carbonatite stock are found southwest of the fault; the magnetite-ilmenite-perovskite segregations and the nepheline syenite seem to be restricted to the northeast side of the fault. Diabase dikes of Ordovician or Cambrian age mainly intrude rocks of the complex on the northeast side of the Cimarron fault, although one diabase dike does cut fenitized Powderhorn Granite just southwest of the fault (Olson, 1974).

Carbonatite dikes, probably similar in age to the carbonatite stock, intrude all rocks of the complex except the carbonatite stock and the Precambrian host rocks, especially those within the fenitized aureole. Martite-fluorapatite veins and jasper-rich veins, the latter probably representing silicified fracture zones, are found intersecting the carbonatite stock. Rocks of the complex and the surrounding area have been mapped in detail by Hedlund and Olson (1968, 1975) and Olson (1974).

Many aspects of the alkalic complex at Iron Hill suggest that it is a representative of the Ijolite series as defined by Bailey (1974). Rocks of this series are characteristically undersaturated with respect to silica and contain fairly abundant alkalies. The

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complex at Iron Hill is also representative of the carbonatitic type of alkalic complex as defined by Rock (1976). These complexes are characterized by the occurrence of intrusive rocks such as carbonatite, ijolite, pyroxenite, melilitic rocks, and nepheline syenite, all lacking calcic plagioclase, and are also found occupying the root zones of nephelinitic volcanoes. King (1965) suggested that rocks of this type formed by differentiation from an immediate parental nephelinite-melteigite magma, which maintained silica undersaturation with a trend toward enrichment of lime, alkalies, and volatiles. With increasing concentration of these components, a point was reached whereupon a highly mobile fraction of alkali and calcium carbonates separated from the crystallizing silicate phase, forming a carbonatite melt. Initially the melt contained abundant alkali carbonates, which allowed the carbonatite to remain as a liquid at low temperatures and pressures, according to King. The presence of fenitized country rocks reflects the alkali content of the melt and shows that alkalies were removed from the melt through reaction with the host. The final product was a carbonatite probably not unlike that found at Iron Hill.

Potentially economic deposits of a number of mineral commodities are known to be associated spatially and genetically with the alkalic complex at Iron Hill. Olson and Wallace (1956) discuss the occurrence of thorium and rare-earth minerals, the thorium mainly concentrated in veins and shear zones outside of the complex, the rare earths mainly in carbonatite dikes and in the Iron Hill carbonatite stock. Hedlund and Olson (1961) identify four

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environments containing thorium, niobium, and rare-earth minerals in the Powderhorn district: (a) carbonatite, (b) magnetite-ilmenite-perovskite bodies, (c) thorite veins, and (d) trachyte porphyry dikes. The magnetite-ilmenite-perovskite segregations were discussed as early as 1912 (Singewald, 1912) as a source of iron and titanium. Rose and Shannon (1960) reported an average grade of 6.5 percent titania and 11.7 percent iron and a possible tonnage in excess of 100 million tons in pyroxenites containing the segregations. In the February 25, 1976, issue of the Denver Post newspaper, Buttes Gas and Oil Co. announced results of a study that indicated 419 million tons of reserves averaging about 12 percent TiO_2 occurred at Powderhorn. Earlier studies of the carbonatite stock by E. I. DuPont de Nemours and Company (Temple and Grogan, 1965) indicated a niobium reserve of over 100,000 tons of Nb_2O_5 in rocks averaging at least 0.25 percent Nb_2O_5. Vermiculite deposits are found in altered pyroxenite, but data on reserves are not available.

The carbonatite stock at Iron Hill

Various modes of origin have been proposed for the carbonatite stock at Iron Hill, the largest exposed massive carbonatite in the United States. Larsen (1942) considered the "marble" of Iron Hill to be the oldest rock of the alkalic complex. He felt that there were no data that suggested an igneous origin for the carbonate rocks and preferred a hydrothermal origin with deposition occurring in a volcanic throat and later modification due to subsequent intrusion of other rocks of the complex. The first application of the term

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"carbonatite" to the Iron Hill carbonate rocks appears to have been by Wallace and Olson (1956); the term "stock" for the form of the massive carbonatite, implying an igneous intrusive origin, was first used by Hedlund and Olson (1961). Temple and Grogan (1965) ascribed a mode of origin based on metasomatic modification of country rock by a CO_2-rich phase associated at depth with volcanic activity. Carbon isotopic data from the Iron Hill carbonatite (Taylor and others, 1967) are similar to values found in diamond, indicating that the CO_2 in the carbonatite had a deep-seated igneous source. The carbon isotopic data and oxygen isotopic data from the Iron Hill carbonatite both fall within the field of primary igneous carbonatite defined by Taylor and others (1967). Strontium isotopic data from various lithologies within the alkalic complex, including carbonatite (Powell and others, 1966), indicate that the rocks within the complex are comagmatic. Strontium isotopic values also suggest that carbonatite-alkalic rock associations, such as that observed at Iron Hill, are mantle derived. Analyses of calcite-dolomite and pyrite-pyrrhotite mineral pairs by Nash (1972) indicate crystallization temperatures between 435^oC and 290^oC for late-stage carbonatites. Samoylov (1975) determined formation temperatures of Iron Hill carbonatite at 600^oC using biotite-pyroxene geothermometry and at 400^oC using amphibole-pyroxene geothermometry.

METHODS OF STUDY

Distribution of thorium in the Iron Hill carbonatite stock was determined by field measurements of thorium abundances at 173 stations within or immediately adjacent to the carbonatite.

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Measurements were made with a Geometrics[1] model DISA-400A portable differential four-channel gamma-ray spectrometer. This instrument uses a 7.6-cm (centimeter)-diameter by 7.6-cm-thick sodium iodide crystal as a detector. Counting times at each station were 2 minutes duration. The instrument was calibrated using an external ^{137}Cs source, and the detector was held 0.5 meters above the ground surface.

In order to relate the instrument count rate on the thorium channel of the spectrometer to thorium abundance, the following formula was used:

$$eTh = 0.094 (C_{Th} - b_{Th}),$$

where C_{Th} represents counts per minute on the thorium channel and b_{Th} represents counts per minute (cpm) background. The b_{Th} was measured over standing water and mainly represents cosmic ray-counts, which for this study is taken as 40 cpm. The value 0.094 is a sensitivity constant derived from a least-squares fitting procedure of measurements made over an area of known thorium abundance by J. S. Duval (written commun., 1976). Drift was checked by periodically returning to a base station and repeating the counting operation at a fixed location. Precision was determined by repeated measurements, after correction for drift, at the base station during the course of the field study. A total of 84 measurements, each of 2 minutes duration, average 769±67 counts. An attempt was made to evaluate

[1]Use of a brand name in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

accuracy by analyzing samples of carbonatite from 28 stations by laboratory gamma-ray spectrometric techniques. The laboratory analyses averaged 47 ppm Th, whereas field measurements at the same localities yielded analyses averaging 38 ppm Th. According to Hansen (1975), the gamma-ray spectrum observed in the laboratory is different from that observed in the field, the latter being strongly influenced by the interaction of gamma rays emitted within the rocks. Inconsistencies also result from the differences in the geometry of the field and laboratory environments. A much greater volume of rock is scanned in the field than in the laboratory. Thus, the accuracy of the field method is difficult to evaluate by comparison with laboratory data.

In addition to being analyzed for potassium, thorium, and uranium by laboratory gamma-ray spectrometric techniques, the samples of carbonatite collected from 28 localities were also analyzed for 61 elements by semiquantitative spectrographic techniques. Splits of the same samples were processed by routine heavy-liquid and magnetic-separation methods, and the component minerals were identified either by physical characteristics or by X-ray powder diffraction methods. Thin sections of the rocks were also studied by routine petrographic techniques.

MINERALOGY AND GEOCHEMISTRY OF CARBONATITE

The mineralogy of the samples collected from the carbonatite stock during this study is not complex. The variety of minerals is somewhat less than that found in the neighboring carbonatite dikes. X-ray and optical studies show the presence of the following

minerals, listed approximately in the order of their frequency of
occurrence: dolomite, barite, goethite, hematite, calcite, quartz,
fluorapatite, pyrochlore, pyrite, magnetite, biotite, rutile,
fluorite, bastnaesite, aegirine, anatase, sphalerite, synchisite,
zircon, magnesite(?), and manganese oxide minerals. The dolomite
occurs as clear, colorless to milky-white grains and as brown,
ferric-oxide-rich grains often described as ankeritic or sideritic by
Temple and Grogan (1965), Hedlund and Olson (1975), and Olson
(1974). Neither ankerite nor siderite was identified in the current
study although siderite occurs in carbonatite dikes adjacent to Iron
Hill. Barite occurs as disseminated colorless grains scattered
throughout the dolomite matrix in highly variable amounts. Goethite
most commonly occurs as shiny, dark-reddish-brown, conchoidally
fractured grains entirely or partly replacing pyrite and forming
pseudomorphs after pyrite. Hematite may be associated with goethite
but also appears to form pseudomorphs after magnetite. This pattern
of occurrence is especially apparent in the martite-fluorapatite
veins that cut the carbonatite stock. Calcite is found in the
carbonatite, but its paragenesis is difficult to determine because of
its similar appearance to dolomite. Small rounded quartz grains are
seen within some dolomite grains. Fluorapatite occurs as clear,
colorless grains in widely variable amounts. Although chemical
analyses are not available, the fluorapatite is suspected to contain
abundant rare-earth elements. Pyrochlore occurs in a variety of
colors including light gray, purplish gray, pink, and pale lemon
yellow to greenish yellow. Pyrochlores analyzed by Nash (1972)

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contain up to several percent ThO_2. However, alpha counter measurements of pyrochlore separates show that not all are radioactive and that there is no correlation between color and radiation. Additional studies of pyrochlore are in progress. Pyrite is a common constituent but is frequently at least partly replaced by goethite. Biotite occurs in streaks at places within the carbonatite, helping to define a foliated variety, and magnetite occurs disseminated throughout the carbonatite. The remainder of the minerals listed earlier are sparse and are seldom seen either in thin sections or in mineral separates. The minerals that have been found in each sample are listed in Armbrustmacher and Brownfield (1979).

The abundance of a variety of elements in 28 samples of Iron Hill carbonatite, the average element content of igneous rocks of the upper continental crust (Wedepohl, 1971, table 7.3), and the average composition of carbonatites (Gold, 1963) are given in table 1. Histograms showing the frequency distributions of elements are presented in figure 2. In comparison with average igneous rocks, the Iron Hill carbonatite contains greater than 20 times more Ba, Ce, and Nd, 15-20 times more La, Nb, P, and ΣREE, and nearly 10 or more times Mn, Mo, and Sr. There is 4.2 times more Th and 3.1 times more RaeU. According to Heinrich (1966, p. 222) characteristic elements found in carbonatites and associated alkalic rocks in general include Ti, Nb, Zr, rare earths of the Ce subgroup (La, Ce, Nd, Pr, Sm, and Eu), P, F, Ba, Sr, and Th. All these elements except Ti and Zr occur in large average concentrations in the Iron Hill carbonatite relative to average igneous rocks. However, abundant Ti occurs in the

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Table 1.--Abundance of elements in the carbonatite at Iron Hill,
the igneous rocks of the upper continental crust,
and the average carbonatite

[Values are in percent. Dashes signify that data are not
available]

Element	Average Iron Hill carbonatite	Average igneous rocks of upper continental crust (Wedepohl, 1971)	Average chemical composition of carbonatites (Gold, 1963)
Fe.........	5.4	3.54	5.12
Mg.........	4.3	1.39	3.40
Ca.........	10.	2.87	25.10
Ti.........	.3	.47	.48
Mn.........	.58	.069	.47
Ba.........	1.56	.059	.23
Be.........	.0007	.0002	--
Co.........	.0018	.0012	.0017
Cr.........	.0065	.007	.0048
Cu.........	.0050	.003	.00025
La.........	.085	.0044	.0516
Mo.........	.0013	.0001	.0042
Nb.........	.040	.002	.1951
Ni.........	.0053	.0044	.0008
Pb.........	.0018	.0015	--
Sc.........	.0015	.0014	.001
Sr.........	.27	.029	.34
V.........	.0050	.0095	--
Y.........	.0037	.0034	.0096
Zr.........	.0064	.016	.112
Si.........	4.4	30.54	5.66
Al.........	.60	7.83	1.88
Na.........	.23	2.45	.31
K.........	1.2	2.82	1.24
P.........	1.2	.081	.90
Ce.........	.17	.0075	.15
Ga.........	.0004	.0017	.0001
Yb.........	.00014	.00034	--
Nd.........	.067	.003	--
Th.........	.0047	.0011	--
RaeU[1]......	.0011	.00035	--
ΣREE[2]......	.34	.0225	--

[1]Radium-equivalent uranium.
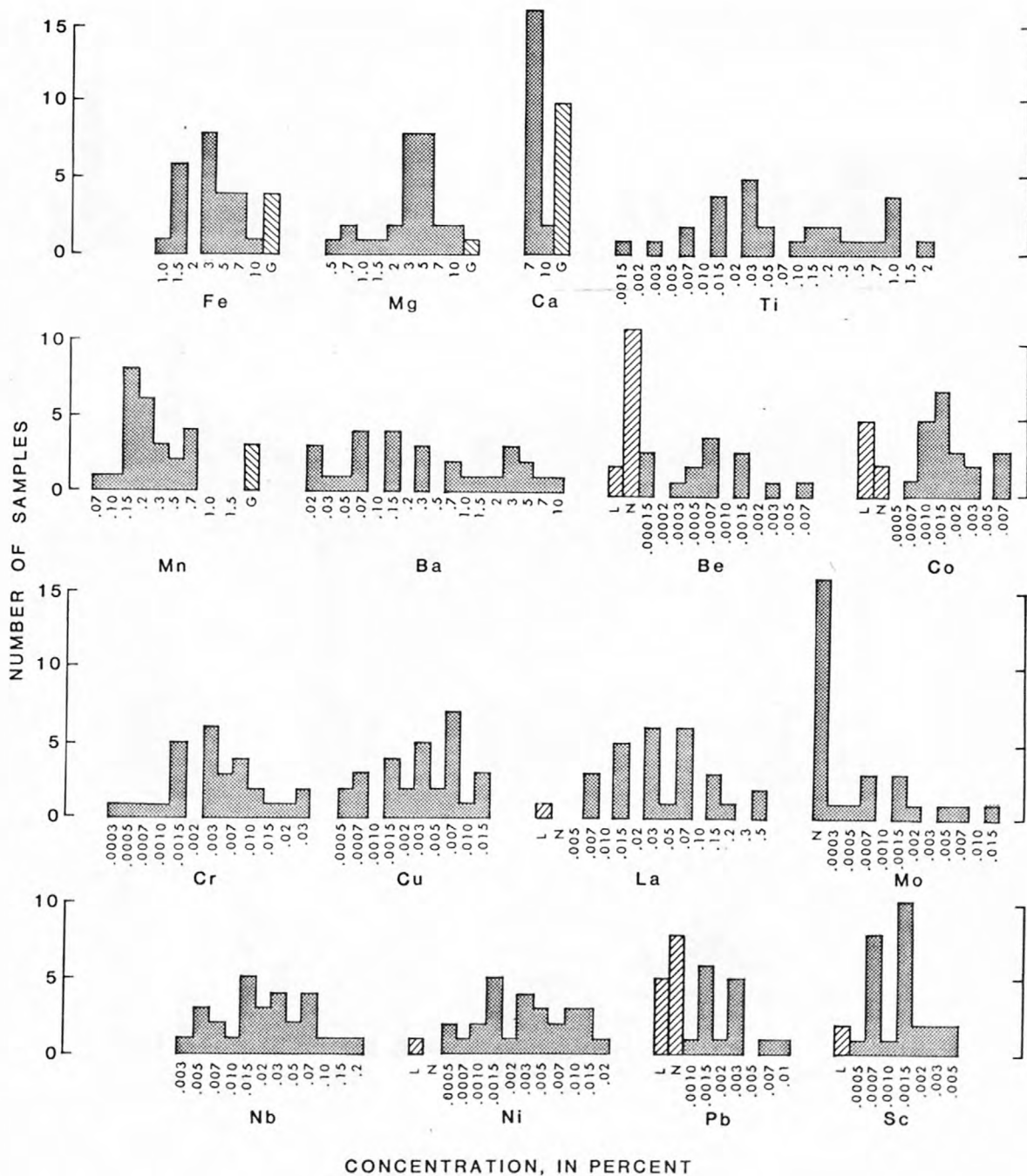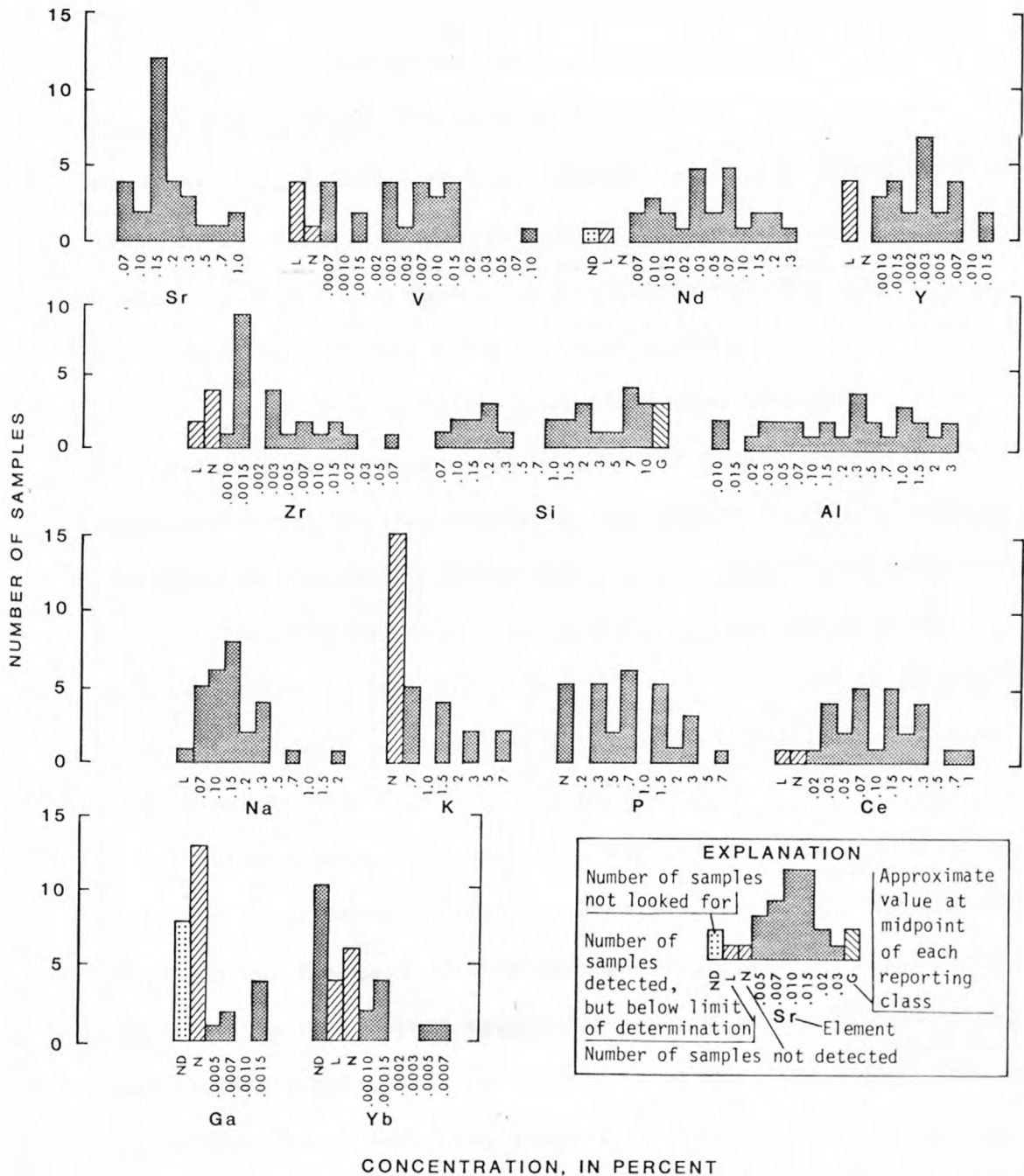[2]Total rare-earth elements.

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Figure 2.-Histograms of elements in 28 samples of the carbonatite at Iron Hill.

NUMBER OF SAMPLES

CONCENTRATION, IN PERCENT

Figure 2 continued.

magnetite-ilmenite-perovskite segregations that are
found in the pyroxenite. The Iron Hill rocks were not analyzed for
fluorine, but fluorite grains appear in a few mineral separates.

When compared with the average composition of carbonatites in
general (Gold, 1963), the Iron Hill carbonatite contains at least 4
times more Ba, Cu, Ni, and Ga. It also contains at least 3 times
less Mo, Nb, Y, Zr,and Al. The remaining elements occur in amounts
similar to Gold's averages. The analytical data for each sample are
given in Armbrustmacher and Brownfield (1979).

Abundance and distribution of thorium

Although many carbonatite occurrences around the world are
anomalously radioactive, available data suggest that the overall
abundance of thorium in carbonatites is not great and that there are
probably few carbonatite bodies in which thorium would be of
principal economic interest. Thorium, however, could be an important
byproduct in those carbonatites being exploited chiefly for niobium
or rare-earth elements.

Thorium appears to have a wide variation in carbonatites in
general. Gerasimovskiy (1973) reports 1.8 ppm Th (0.0002 percent
ThO_2) for the Kerimasi carbonatite and 46.8 ppm Th (0.0053 percent
ThO_2) for the Fort Portal carbonatite; these values represent average
compositions for East Africa rift-zone carbonatites. That part of
the carbonatite at Palabora, Transvaal, that constitutes the copper
orebody contains about 0.033 percent Th (0.038 percent ThO_2) (Hanekom
and others, 1965). The Sulfide Queen carbonatite at Mountain Pass,
California, contains an average grade of 0.026 percent ThO_2 (Shawe,

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1953). Primary magmatic carbonatite dikes in the Wet Mountains area, Colorado, average 0.18 percent Th (0.20 percent ThO_2) (Armbrustmacher, 1979). The thorium content of carbonatite at Magnet Cove, Arkansas, appears to be very low (Erickson and Blade, 1963) and does not exceed about 35 ppm Th (0.004 percent ThO_2) in any rock within the entire alkalic complex. Data on several other carbonatite localities are given by Olson and Overstreet (1964).

Occurrences of anomalous amounts of thorium in rocks of the Powderhorn district have been known since 1949 (Olson and Wallace, 1956). Wallace and Olson (1956) point out the presence of at least one locality within the Iron Hill carbonatite stock characterized by anomalous radioactivity, and Hedlund and Olson (1961) indicate that the carbonatite stock has a maximum radioactivity 5 times greater than background. Temple and Grogan (1965) indicate that "typical foliated carbonatite" in the carbonatite stock averages 0.01-0.02 percent Th (0.011-0.023 percent ThO_2).

Data gathered in the current study are summarized in figure 3. This histogram shows the variation in 173 thorium analyses of carbonatite in the Iron Hill stock. The average thorium value is 36.2 ppm Th (0.0041 percent ThO_2). The median value is 31 ppm Th (0.0035 percent ThO_2); the minimum value is 6 ppm (0.0007 percent ThO_2) and the maximum value is 150 ppm (0.017 percent ThO_2).

The distribution and variation of thorium in the Iron Hill stock is portrayed by the contour map in figure 4. Using a contour interval of 10 ppm Th, several areas of stronger concentration of Th are outlined. Especially noteworthy are the areas just west of the
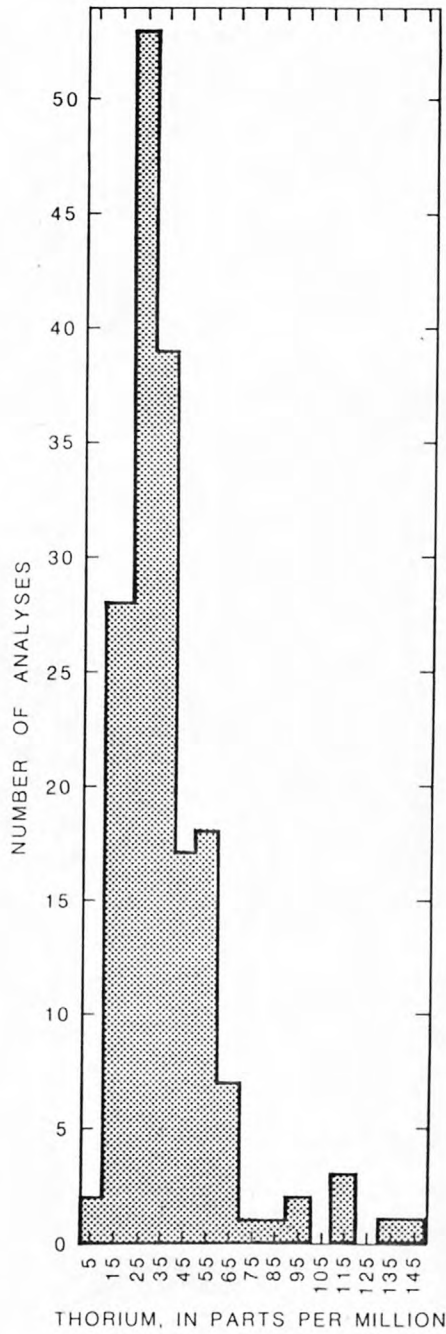
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Figure 3.-Histogram of frequency distribution of 173 thorium values,
   in parts per million, determined by field gamma-ray spectrometry,
   from the Iron Hill carbonatite.

EXPLANATION

x Locality of field
   gamma-ray spectrometer
   measurements

△ Geochemical and mineralogical
   sample locality and field
   gamma-ray spectrometric
   reading

——Contact between carbonatite
   (including carbonatite-rich talus)
   and alkalic rocks (including alluvium)

——Contours of equal thorium content

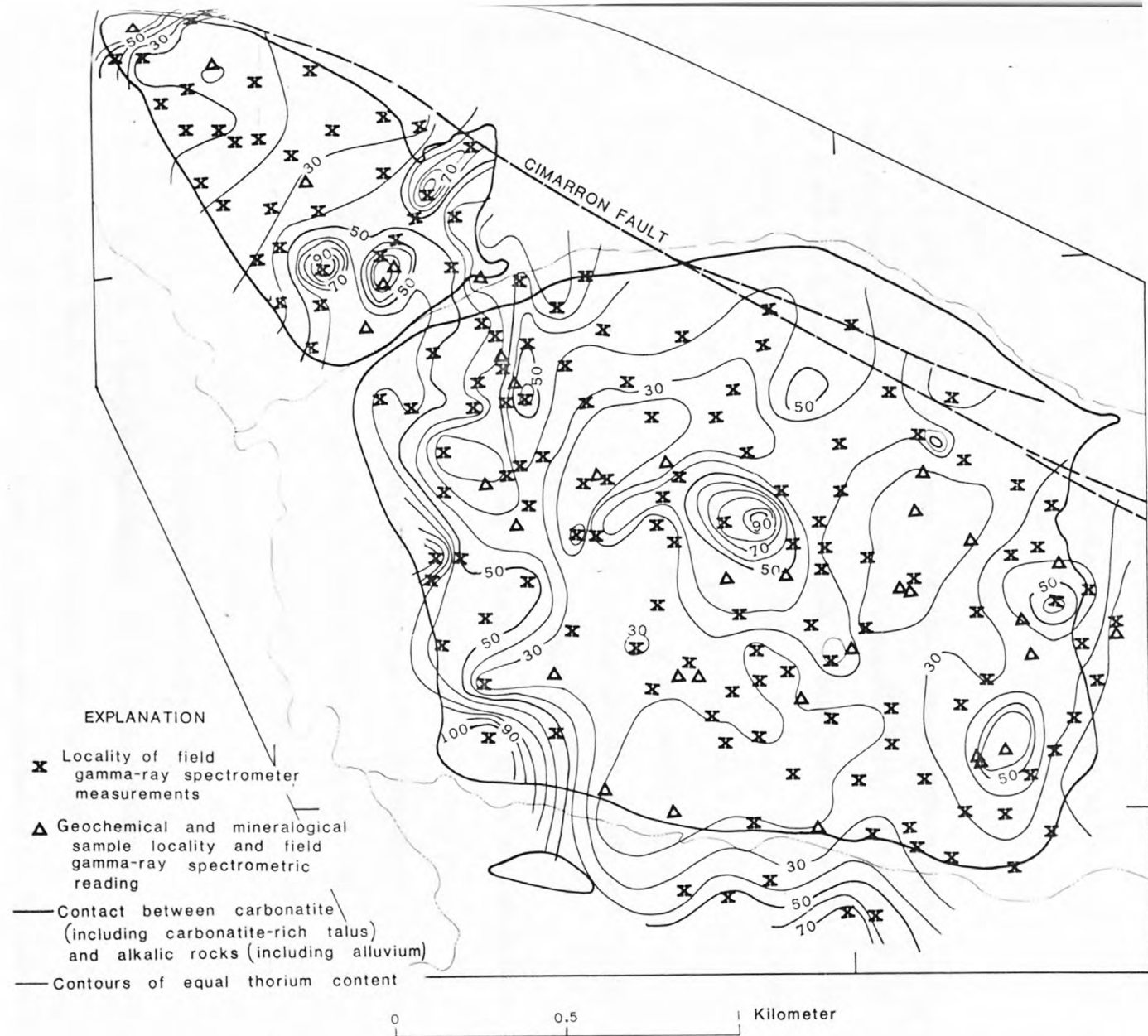CIMARRON FAULT

0   0.5   Kilometer

Figure 4.-Contour map of thorium distribution in the carbonatite at
Iron Hill.

summit of Iron Hill and at the southwest corner of the stock.

The areas containing stronger concentrations of thorium do not correspond to areas known to contain more abundant niobium, such as the area around the DuPont adit and the area immediately north of Beaver Creek (James V. Thompson, oral commun., 1977). Temple and Grogan (1965, p. 680) also point out the lack of general correlation between radioactivity and niobium occurrence. Using analyses of the 28 samples of carbonatite, correlation coefficients were calculated in order to test the strength of associations among thorium, niobium, total rare earths, and uranium. A perfect correlation would be 1.0, a perfectly random association would be 0.0. Results give Nb-REE, 0.41; Nb-V, 0.18; Nb-Th, 0.10; U-Th, 0.59; REE-Th, 0.50; and REE-U, 0.19. Although based on data insufficient to support generalizations, it is interesting to note that the niobium-thorium association shows the weakest correlation. Alpha-counter measurements of mineral separates show moderate amounts of radioactivity, 5-10 counts per minute above background, in some of the pyrochlore concentrates. None of the other minerals in the carbonatite appears to be radioactive.

RESOURCE ASSESSMENT

As part of a program to assess the thorium reserves of the U.S., funded by the U.S. Department of Energy, the Minerals Availability Field Office of the U.S. Bureau of Mines was requested to design cost analyses of mine and mill models for the recovery of thorium from massive carbonatite deposits. The details of the procedures, which are only outlined here, can be found in Staatz and others (1979).

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The cost analyses provide for an open-pit mining procedure with recovery of thorium based on flotation of pyrochlore, followed by chlorination, acid leach, and a solvent extraction procedure. Byproducts of the procedure are uranium, niobium, and rare-earth elements. It is assumed that thorium, uranium, niobium, and rare-earth elements occur together in the pyrochlore. Mining costs are subdivided into capital costs, which include mine development, mine structures, and mine equipment; and operating costs, which include materials, utilities, labor, and maintenance, as well as taxes and insurance. Milling costs are also subdivided into capital costs and operating costs. These four items are represented by curves that fit a range of 1,000-10,000 tons per day mining capacity with the maximum value of 10,000 tons per day used in the cost calculations. A maximum mill life or mine life of 15 years is assumed so that the maximum tonnage that can be handled is 52,500,000 tons (10,000 tons/day x 350 days/year x 15 years).

Various methods can be used to determine the amount of carbonatite at Iron Hill that might be potentilly economically important. In this study, the following method used to determine the amount of carbonatite that projects above the surrounding land surface. Seven evenly spaced cross sections were constructed across the carbonatite stock, the area was measured in each cross section, and the average area in each pair of sections was multiplied by the distance between them. Using this method, Iron Hill was found to contain 722,700,000 short tons of carbonatite[2]. Based on the field gamma-ray spectrometric readings, the average thorium concentration

is 0.0041 percent ThO_2, which yields 29,775 tons of ThO_2 in the carbonatite. Assuming the abundance of elements in the 28 analyzed samples to be representative of the entire carbonatite stock, the stock would contain 9,180 tons of U_3O_8 (avg. 0.00127 percent), 2,865,500 tons total rare-earth oxides (avg. 0.3965 percent) and 412,000 tons Nb_2O_5 (avg. 0.057 percent). Higher grades of thorium and the coproduct elements could be obtained by selective mining because the distribution of each element is not consistent within the stock. Staatz and others (1979) define these values as reserves. Carbonatite defined as probable potential resources by Staatz and others (1979) is considered to extend an additional 800 feet in depth. With a map area of 38,070,000 ft^2 (square feet), 2,672,000,000 short tons of carbonatite containing 110,090 tons of ThO_2, 33,930 tons of U_3O_8, 10,590,000 tons of total rare-earth oxides, and 1,523,000 tons of Nb_2O_5 would fall into that category.

A more generalized way to arrive at tonnage and grade figures would be to calculate the amount of coproducts contained in each vertical foot of carbonatite. With those values one could select any depth and any mining configuration that seemed appropriate. The map area covered by the stock is 38,070,000 ft^2. With a depth of 1 ft, there is 38,070,000 ft^3 (cubic feet) or 3,339,470 tons of carbonatite, and thus 138 tons of ThO_2, 42 tons of U_3O_8, 13,240 tons of total rare-earth oxides, and 1,900 tons of Nb_2O_5 per foot of depth.

The cost of producing ThO_2 from the carbonatite at Iron Hill was

[2]All calculations were made in U.S. customary units as required by the U.S. Department of Energy contract.

estimated in two ways: (1) the cost if ThO_2 is the only product obtained from the carbonatite, and (2) the cost if Nb_2O_5, RE_2O_3 (rare-earth oxides), and U_3O_8 are products in addition to ThO_2. The final cost to mine and mill ThO_2 alone would be $68 per pound. If NbO_5, RE_2O_3, and U_3O_8 were all marketable at current prices, the combined value of these commodities would be more than twice that of ThO_2, assuming ThO_2 could be sold for $50 per pound. It thus appears certain that the economics of ThO_2 contained in the carbonatite stock at Iron Hill are inseparably linked to those of Nb_2O_5, RE_2O_3, and U_3O_8.

SUMMARY

Studies of the occurrence of thorium in the carbonatite at Iron Hill show a fairly inhomogeneous distribution with values ranging between 6 ppm Th (0.0007 percent ThO_2) and 150 ppm Th (0.017 percent ThO_2); several local anomalies occur. The average thorium content of the carbonatite, the value used in the resource calculations, is 36.2 ppm Th (0.0041 percent ThO_2). Comparisons with other potential sources of thorium, such as the vein deposits in the Lemhi Pass district, Idaho and Montana (Staatz, 1972), and in the Wet Mountains, Colorado (Armbrustmacher, 1976; Christman and others, 1959), and the disseminated deposits at Hicks Dome, Illinois (Brown and others, 1954), and Bear Lodge Mountains, Wyoming (M. H. Staatz, written commun., 1978), show that the carbonatite at Iron Hill contains considerably less total reserves (Staatz and others, 1979, table 1). Therefore, the economic future of thorium at Iron Hill appears to be closely tied to the economics of niobium and rare earths.

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