The Morro do Ferro Thorium and Rare-Earth Ore Deposit, Poços de Caldas District, Brazil

GEOLOGICAL SURVEY BULLETIN 1185-D

Prepared on behalf of the U.S. Atomic Energy Commission in cooperation with the Commissão Nacional de Energia Nuclear, Brazil

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By HELMUTH WEDOW, JR.

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By HELMUTH WEDOW, JR.

ABSTRACT

Rare-earth elements and thorium are closely associated with a large magnetite stockwork cutting alkalic igneous rocks at Morro do Ferro on the Poços de Caldas Plateau in southern Brazil. The ore deposit was discovered in 1953 by the ground search for an area of very high radioactivity recorded during an airborne survey of the plateau. Shortly after the discovery of the deposit, drilling and tunneling were started to determine the subsurface limits and grade of the ore body. In 1955 a surface exploration program was conducted to determine the character, grade, and tonnage of near-surface material that might be developed by large-scale open-pit mining methods.

The near-surface material at the Morro do Ferro deposit is laterite developed by the deep tropical weathering of syenite-phonolite rocks, locally enriched with thorium and the rear-earth elements in the vicinity of the magnetite veins of the stockwork. The major vein system of the stockwork trends about N. 55° W. and dips steeply to the northeast. Allanite was probably the major primary-rare earth-bearing radioactive mineral impregnating the alkalic rocks in the stockwork; however, laterization has altered most of the allanite to a powdery, porous, yellowish- to reddish-brown claylike material that contains most of the thorium and rare earths. Recognizable secondary minerals produced by the weathering of the allanite include bastnaesite, cerianite, and thorogummite.

The trenching and test-pitting of the exploration program opened enough of the surficial parts of the stockwork to outline a highly radioactive northwest-trending lenticular zone on the southeast side of Morro do Ferro. This zone with a length of about 500 meters and a maximum width of about 130 meters, is surrounded by a halo of moderately radioactive material as much as several tens of meters broad. Gamma-ray probing of open drill holes indicates that both zones extend to depths of 10–15 meters and that radioactivity declines slightly with depth. At greater depths the more highly radioactive material becomes very spotty or pockety. The near-surface part of the central enriched zone is calculated to contain about a million metric tons of material with an average grade approaching 1 percent thoria and 4 percent total rare-earth oxides. The halo zone surrounding this central area probably contains about half a million metric tons averaging close to ½-percent thoria and 1½–2½ percent total rare-earth oxides.

The Morro do Ferro deposit has promise as a source of thorium and the rare earths. The extremely large tonnages of the enriched, relatively soft, decomposed rock and laterite can be readily worked with mechanized earthmoving equipment. The chief difficulty will be in beneficiating or extracting the thorium and rare earths in a manner that will be competitive with other sources of these elements.

INTRODUCTION

Mineral rights at Morro do Ferro (Iron Hill) (originally called "Morro Alto e Consulta"), in the Minas Gerais part of the Poços de Caldas Plateau, Brazil (figs. 1, 2) were acquired by the Companhia Geral de Minas in April 1935 for iron and associated metals. It was not until 1953, however, that the strong radioactivity of the deposit was recognized. The discovery of the radioactivity was made during the airborne scintillation-counter survey made of the Poços de Caldas Plateau by Levantamentos Aérofotogramétricos, S.A. (hereafter referred to as LASA) with the technical assistance of Aero Service Corporation, Philadelphia (Tolbert, 1966). The relation of the Morro do Ferro anomaly to the other principal anomalies in the district is shown in figure 2. Preliminary ground investigation of the Morro do Ferro area, made by geologists of the U.S. Geological Survey (USGS) in collaboration with members of the Brazilian Conselho Nacional de Pesquizas (CNPq) and Departamento Nacional da Produção Mineral (DNPM), showed that the intense surface radioactivity was associated with laterite and other surficial deposits developed on the alkalic igneous rocks of the plateau where these rocks are associated with a stockwork of magnetite veins. Analyses of samples collected during the preliminary surface studies [1] indicated that the radioactivity is due almost entirely to thorium and its daughter products in a rare-earth deposit. Subsequently, the DNPM began an exploration program to determine the grade and tonnage of the deposit. From June to September 1955 the Cia. Geral de Minas conducted a surface-trenching program with the collaboration of the CNPq and the USGS, primarily to obtain the tonnage and grade of material in the near-surface parts of the deposit.

The information available to the writer, prior to the trenching program, was summarized by G. E. Tolbert (see footnote 1). The present report discusses the results of the trenching program and the gamma-ray logging of those holes drilled by the DNPM that were sufficiently open to permit probing with scintillation-detection equipment. The results of preliminary mineralogical studies are also presented. Short reports summarizing the findings on which this study is based have already been published (Oliveira, 1956; Wedow, 1961a).

The author wishes to express his appreciation to the Companhia Geral de Minas for help extended during the investigation. Dr. H. O. J. Penido, manager, was especially cooperative and placed the full facilities of the company at the disposal of the author. The assistance of the DNPM at Poços de Caldas and Rio de Janeiro is also gratefully

[1] Tolbert, G. E., 1955, Preliminary report on the Morro do Ferro thorium-bearing rare-earths deposit, Poços de Caldas Plateau, Brazil: Unpub. rept. prepared for Conselho Nacional de Pesquizas, Brazil.

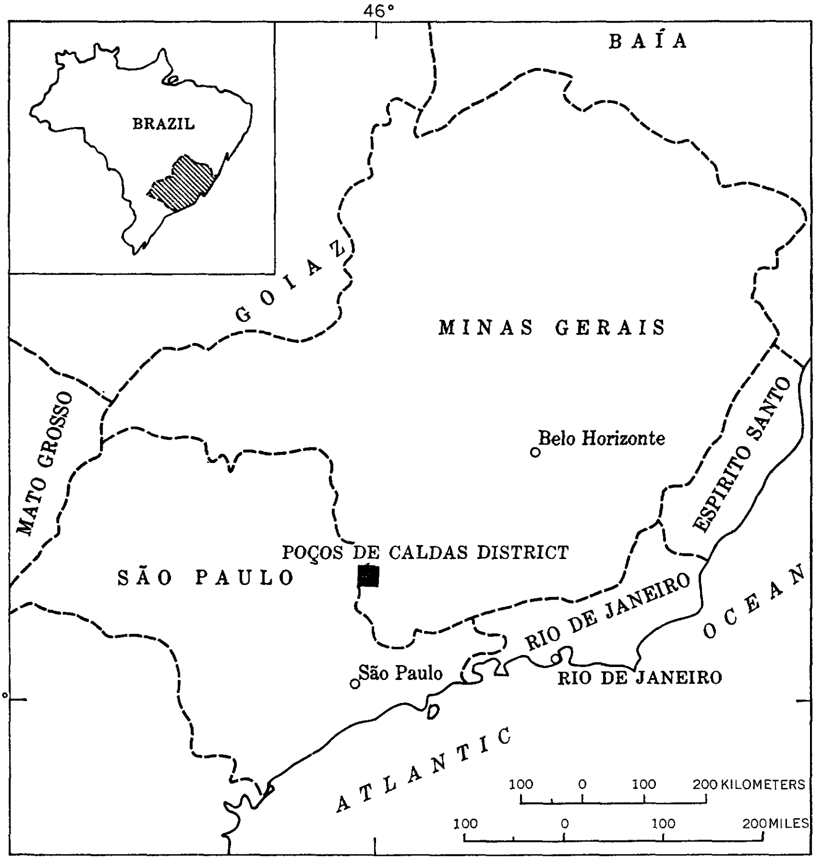

FIGURE 1.—Location of the Poços de Caldas district.

acknowledged. Max G. White and Gene E. Tolbert of the USGS were associated with the author in the investigations.

This report concerns work performed by the Brazilian Conselho Nacional de Pesquizas and subsequently by the Brazilian Commissão Nacional de Energia Nuclear and the United States Geological Survey on behalf of the United States Atomic Energy Commission, and it is published with the approval of these agencies.

GEOGRAPHIC AND GEOLOGIC SETTING

The Poços de Caldas district lies on the border of the States of São Paulo and Minas Gerais in southeastern Brazil (fig. 1). It consists of a roughly circular plateau that has an area of about 1,000 square kilometers (fig. 2) and an average altitude of about 1,300 meters. The rolling, grass-covered hills of the plateau are bordered by a rim of mountains whose peaks attain heights of 1,600–1,800 meters. The low-

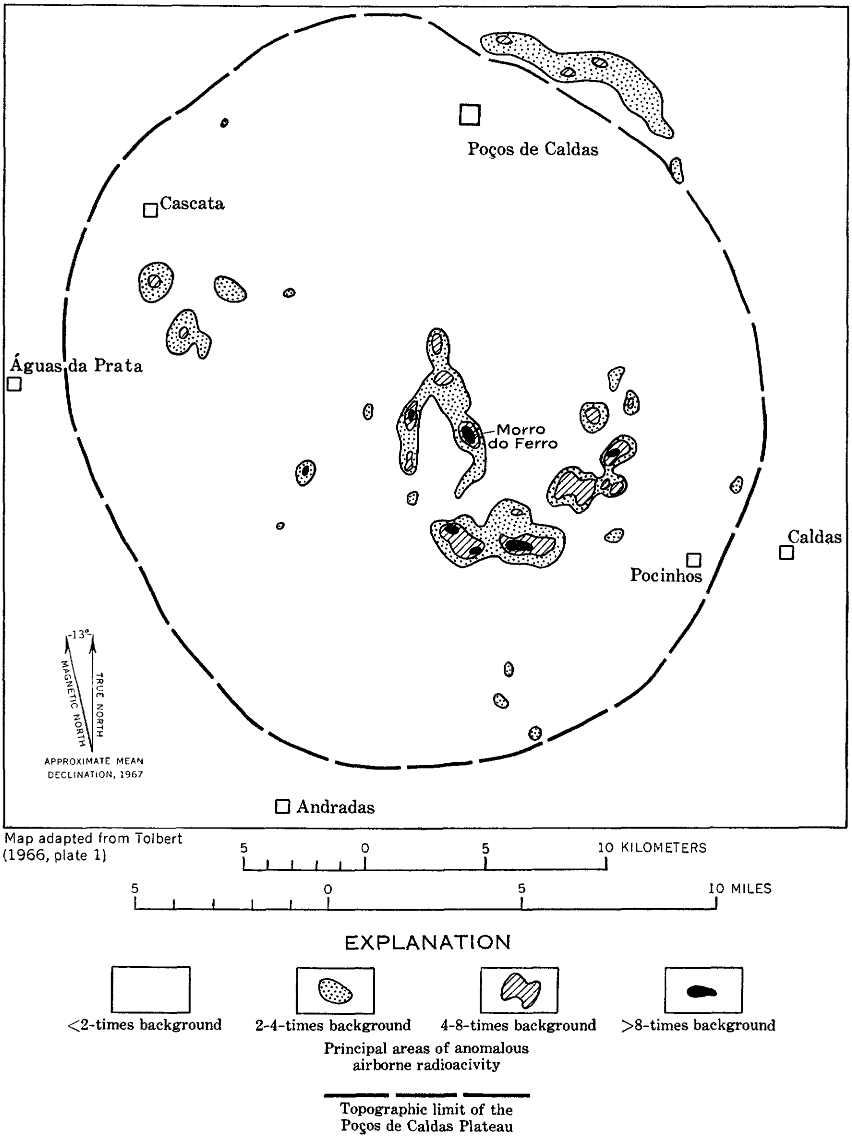

FIGURE 2.—Sketch map of the Poços de Caldas district, showing principal areas of anomalous airborne radioactivity and the location of Morro do Ferro.

lands surrounding the mountains reach altitudes of 800–900 meters. The relief of the western half of the plateau is less than that of the eastern half. The highest point of the plateau is Morro do Ferro, which has an altitude of 1,541 meters.

Poços de Caldas (population about 24,000 in 1955), the principal town on the plateau, is connected to São Paulo by both rail and highway. Rail service from São Paulo, a distance of about 310 kilometers, is by the Estrada de Ferro Mogiana, a narrow-gage railroad. The highway from São Paulo (275 km) is an all-weather road. Regularly scheduled airline flights connect Poços de Caldas with Rio de Janeiro, Belo Horizonte, and São Paulo.

The bedrock of the Poços de Caldas district consists principally of alkalic intrusive rocks, chiefly nepheline syenite and phonolite; other rocks include breccia, agglomerate, tuff, and sandstone. In many localities on the plateau the bedrock is deeply weathered; as a result, lateritic deposits rich in aluminum, iron, and manganese oxides are common. Zirconium ores are present in significant quantity and, with bauxite, have been the chief mineral exports of the district (Teixeira, 1936 and 1937).

Morro do Ferro (fig. 3) is near the geographic center of the Poços de Caldas district and is about 15 kilometers due south of the town of Poços de Caldas (fig. 2). It is roughly elliptical, trends northeasterly, and has a relief of about 140 meters and a maximum diameter of about 1 kilometer. The summit altitude is 1,541 meters. The hill is devoid of vegetation except for grasses and low bushes. A small densely wooded area lies along the small stream draining the base of the south slope. Access to the Morro do Ferro area is by dirt road and trail, a distance of about 21 kilometers from Poços de Caldas.

At Morro do Ferro the country rock is too decomposed to be identified in the field, but it was probably part of the syenite-phonolite complex of alkalic igneous rocks which characterize the Poços de Caldas district. The syenite-phonolite rocks are cut by a network of magnetite veins which form a northwesterly-trending stockwork. It is likely that the magnetite represents an extremely late stage in the intrusion. During the intrusion of the stockwork the country rock was apparently brecciated and altered. The alkalic rocks cut by the stockwork, and to some extent the magnetite veins themselves, were enriched by mineralizing solutions containing chiefly the rare-earth elements and thorium. Whether the original thorium and rare-earth minerals were deposited contemporaneously with the magnetite, as at the Scrub Oaks mine in New Jersey (Klemic and others, 1959, p. 55), or were deposited later is not known. Subsequent deep weathering, typical of the region as a whole, altered the rare-earth- and thorium-enriched alkalic rocks of the ore deposit and the adjacent unenriched rocks as well, to a compacted clayey lateritic material with local relict structures and textures. The depth of this weathering is not known but may extend more than 100 meters below the present surface, although remnant blocks of relatively less weathered material may be scattered throughout the weathered mantle of the hill. Eluvial concentrations of magnetite rubble, ranging in depth from a few

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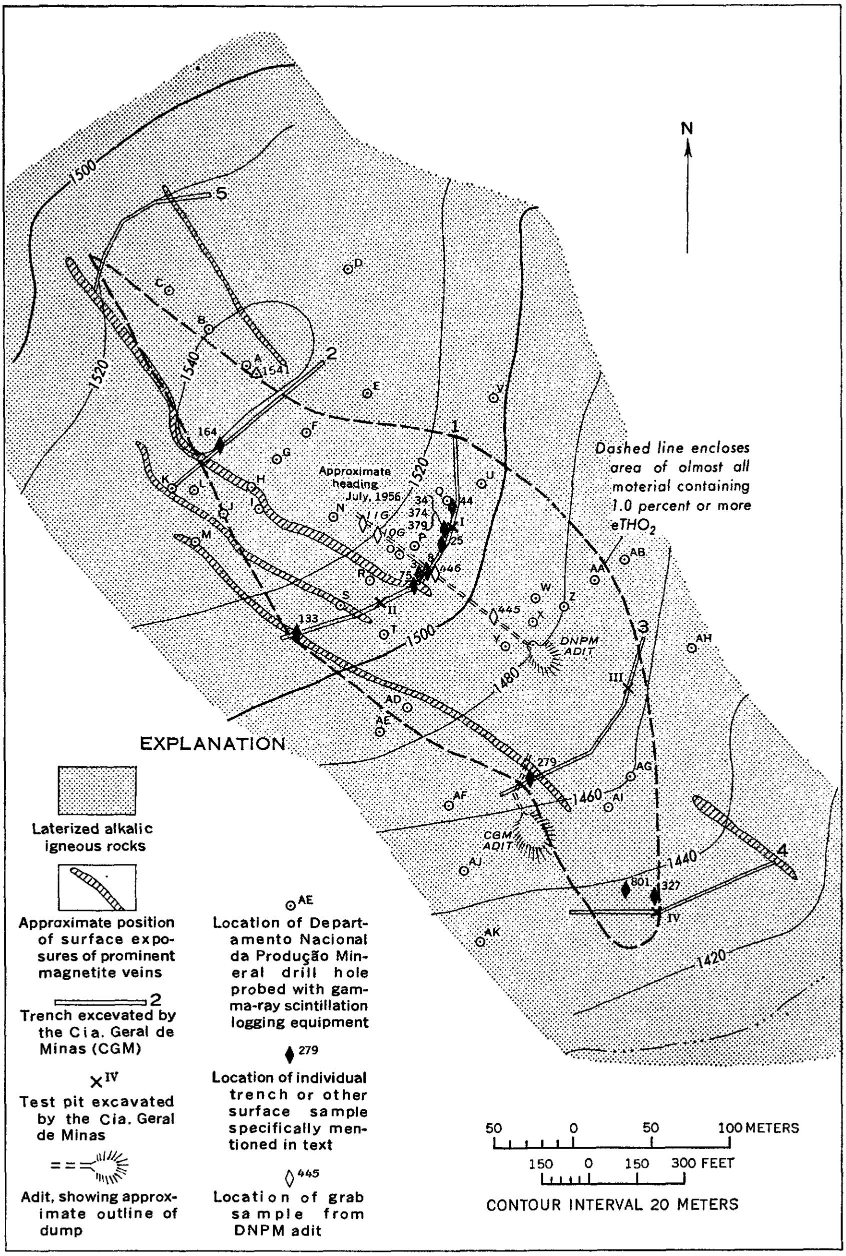

FIGURE 3.—Topographic and geologic sketch map of Morro do Ferro thorium and rare-earth ore deposit, showing location of trenches, test pits, and selected DNPM drill holes.

centimeters to as much as 2 meters (avg about 30 cm) cover most of the area underlain by the stockwork. Beneath the eluvial mantle of magnetite various weathering processes, chiefly eluviation and laterization, seem to have caused a secondary enrichment of thorium and the rare-earth elements in the near-surface parts of the stockwork. It is with this near-surface enriched zone at Morro do Ferro that this report is primarily concerned.

THE THORIUM AND RARE-EARTH DEPOSIT

The most intense radioactivity at Morro do Ferro is in the near-surface zone of a deeply weathered stockwork in alkalic igneous rocks highly enriched with the rare-earth elements and thorium. The outcrop of the more strongly radioactive material is about 500 meters long and attains a maximum width of about 130 meters (fig. 3). It extends from near the base of the hill on the southeast flank (alt about 1,420 m) to the summit (alt 1,541 m) and thence down the northwest flank to an altitude of about 1,520 meters. The maximum width appears to be at an altitude of about 1,510 meters on the southeast flank of the hill (fig. 3). Although very little is known about the possible depth of the deposit, trenches and test pits show that material containing significant amounts of radioactivity (1.0 percent or more $eThO_2$[2]) exists to depths of 4–5 meters. In places probing of the DNPM drill holes with gamma-ray scintillation logging equipment recorded radioactivity that may be equivalent to 1.0 percent or more ThO_2 at depths ranging from 5 to 30 meters. Slightly less intense radioactivity that may be equivalent to 0.5–1.0 percent ThO_2 occurs from 30 down to about 50 meters. The data from depths below 10 meters, however, are insufficient to determine the depth to which the ore body extends; it is inferred on the basis of the available data that the deposit is chiefly a surficial lateritic enrichment of the stockwork protore.

LITHOLOGY

The country rock at Morro do Ferro seems to have been chiefly phonolite, nepheline syenite, and their porphyritic equivalents. In general, the mineral grains of the original syenite were as much as several millimeters in diameter; where the syenite was porphyritic, the phenocrysts were as much as 1 centimeter long. The phonolites were porphyritic, for the most part, with phenocryst grains as large as several millimeters in diameter in an aphanitic or very finely crystalline groundmass.

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[2] $eThO_2$ is equivalent thorium oxide. It is a measure of the radioactivity and is expressed as the equivalent amount of thorium oxide that would be required to produce the measured radioactivity if the radioactivity were due solely to thorium and its daughter products in equilibrium.

Although no fresh bedrock has been observed on Morro do Ferro, the same rock types elsewhere on the Poços de Caldas Plateau generally are various shades of gray. In the highly compacted laterite in the vicinity of Morro do Ferro, the colors are commonly white to yellow to red brown, depending on the degree of staining by iron oxides; locally some of the weathered material is black because of disseminated manganese oxides. The enriched material of the Morro do Ferro laterite is similar in color but generally is more deeply iron stained; locally small patches are yellowish green, a color which is possibly caused by a high content of rare-earth minerals.

Intense staining by iron oxides is common in the uppermost few centimeters of the radioactive laterite and locally extends to depths of several meters; much of this iron was probably derived from magnetite in the eluvial cover by solution and was redeposited as hematite or limonite. Relict structures and textures, where present, are commonly obscured in areas of intense iron-oxide staining.

STRUCTURE

The radioactive rare-earth deposit at Morro do Ferro is closely associated with the magnetite veins of the stockwork. The major veins strike about N. 50°–60° W. (fig. 3) and dip 50°–85° NE. Although some are as much as 5 meters thick, most are 1–3 meters thick. Other prominent magnetite veins in the stockwork range in thickness from a few tens of centimeters to about 2 meters and have various attitudes, but there is a general tendency for strikes to cluster in the sector N. 10°–35° E. and for dips to range from vertical to 45° either to the northwest or southeast. Numerous magnetite veinlets with thicknesses from a fraction of a millimeter to as much as several centimeters cut randomly through the stockwork and trend in the same general direction as the larger veins. Because of weathering, many of the smaller magnetite veinlets have been altered either completely or partly to limonite. Other limonite veinlets, however, may have been caused by the precipitation of limonite from solutions moving downward along fractures. Manganese has been similarly concentrated in veinlets, either by alteration of original minerals or by introduction of manganese during weathering.

The fracture system containing the magnetite veins and veinlets seems to have controlled the enrichment and amount of thorium and rare-earth mineralization. Evidence supporting this conclusion may still be recognized despite the modifications imposed by laterization. Thus, one of the variously shaped polyhedral blocks of rock on one side of a vein or veinlet may be more radioactive or contain more rare earths than a similar block on the other side of the vein or veinlet. This structural control is exhibited not only by minor structural features but also by the major magnetite veins. In general, the more radioactive parts of the deposit are nearer to or immediately adjacent to the major veins. The distribution of radioactive materials and other field observations seem to indicate that the magnetite veins had a tendency to dam the rising mineralized solutions so that the rocks on their footwall sides became locally more enriched with radioactive minerals than the rocks on their hanging wall sides.

EXPLORATION

The first ground exploration of the deposit at Morro do Ferro was a radioactivity survey made by Gene E. Tolbert and Helem Bessa in 1953 (see footnote 1, p. D2). This survey outlined an area of radioactivity about 400 meters long and 75–100 meters wide of such high intensity that readings could not be recorded by a standard Geiger counter equipped with a 2- by 20-inch gamma probe. At this time the DNPM began exploration of the deposit by drilling more than 100 auger and diamond-drill holes. The auger holes ranged in depth from a few meters to 50 meters, and some of the diamond-drill holes are reported to have reached depths of more than 100 meters. Another phase of the exploration program of the DNPM consisted of driving an adit into the radioactive stockwork at an altitude of about 1,480 meters on the southeast side of Morro do Ferro (fig. 3) and in the general direction of the strike of the major magnetite veins. In July 1956 the working face of the adit was more than 100 meters from the portal.

In April 1955, Tolbert (see footnote 1, p. D2), using scintillation counters, noted a wide variation in the radioactivity over the previously determined zone of high radioactivity and recommended that some surface exploration be done.

In June 1955 the Cia. Geral de Minas undertook an exploration program with the primary objective of determining what surficial parts of the deposit would be amenable to large-scale opencut mining methods. This program consisted chiefly of digging five trenches in a direction essentially normal to the trend of the stockwork (fig. 3). The total length of trenching was about 500 meters. The trenches were generally about ¾–1 meter in width and ranged in depth from less than ½ meter to as much as 2 meters, averaging about 1½ meters. The five trenches crosscut the area of surface radioactivity at altitudes of about 1,430, 1,465, 1,510, and 1,540 meters on the southeast flank of the hill and at 1,520 meters on the northwest flank. The trench sites (fig. 3) were located by the author in May 1955 on the basis of scintillation-counter traverses.

The trenching was supplemented by four test pits that ranged in depth from 3 to 5 meters. The sites of the pits, selected on the basis of results of the trench sampling (described under "Sampling and analyses"), were designed primarily to test the vertical variation in radioactivity several meters below the floors of the trenches. Because of caving, depths greater than 5 meters in the test pits were not considered safe, and an attempt was made to crosscut the deposit with an adit at an altitude of about 1,450 meters (fig. 3). The driving of this adit was also abandoned because of caving. The last reported position of the working face was about 39 meters from the portal. (See fig. 3.)

Measuring radiation in the drill holes tested the radiation to greater depths than it was tested in the trenches and the several test pits. The specially designed scintillation-detection equipment used to probe the holes was the type developed by the USGS for similar drill-hole logging in the uranium deposits of the Colorado Plateau. Of the more than 100 auger and diamond-drill holes bored by the DNPM, only 36 were still open to depths of more than 2 meters at the time of the probing. In most of these holes, probe-depths ranged from 5 to 15 meters, although two reached 47 and 53 meters, respectively. The total depth logged amounted to 385½ meters in the 36 holes. The locations of the holes logged are shown in figure 3.

SAMPLING AND ANALYSES

Variations in grade of near-surface material were determined by traversing with a scintillation counter and sampling in the trenches excavated by the Cia. Geral de Minas. Channel samples were cut in the uphill wall of each trench at an average distance of about 25–30 centimeters above the floors of the trenches. The test pits were sampled by channels in each of the two uphill corners of the pits. The lengths of both trench and pit samples were determined mostly by the variation in radioactivity along the line of sampling, although color and lithologic variation also were considered. The sample lengths ranged from a minimum of about 20 centimeters to as much as 3 meters; most, however, ranged from 60 centimeters to 1.5 meters. Sample weights varied widely, generally depending on the amount of magnetite included, though most were about 5 kilograms. The samples were dried and crushed by the Cia. Geral de Minas to approximately minus 4-mesh. Because of the caving ground in the company adit at 1,450 meters, only about the first 10 meters of the adit could be sampled before it became inaccessible. The company completed channel sampling of all surface openings by September 1955. More than 500 samples were cut in this phase of the program. By the end of 1955 the trenches had been sampled to obtain a bulk sample for beneficiation tests.

RADIOACTIVITY ANALYSES

TRENCH SAMPLES

Preliminary radioactivity analyses were made on the trench samples with a portable scaler at Poços de Caldas using as a standard a sample from Morro do Ferro that had been determined to contain 1.5 percent ThO_2 by the Instituto de Pesquizas Tecnológicas (IPT) in São Paulo. The equivalent thoria content of the 431 trench samples as determined in Poços de Caldas ranged from a low of less than 0.1 percent to a maximum of 2.8 percent. These analyses are given in table 1 under the column headed PdeC.

TABLE 1.—*Radioactivity data and lengths of samples taken from trenches at Morro do Ferro*

Sample: Samples are arrayed in sequence from southwest to northeast for each trench. For example, in trench 1, the southwesternmost sample is MF-139, sample MF-1 is contiguous to MF-75 near the middle of the trench, and MF-74 is the northeasternmost sample from this trench.

Percent $eThO_2$: PdeC, analyses of minus 4-mesh material made with a portable scaler at Poços de Caldas; Rio, radioactivity analyses made on minus 20-mesh material in the DNPM-USGS laboratories at Rio de Janeiro.

Composite group: Groupings of individual trench samples made for calculation of weighted averages and preparation of composite samples (see table 2).

Sample MF-	Length (meters)	Percent $eThO_2$		Composite group
		PdeC	Rio	
Trench 1				
139	1.5	0.2	------	1-1
138	1.5	.3	------	
137	.7	1.4	------	1-2
136	2.0	.9	------	
135	2.0	.9	0.85	
134	1.5	.2	------	
133	1.0	1.5	1.29	1-3
132	1.0	1.3	------	
131	1.1	1.2	------	
130	1.4	1.8	1.77	
129	1.0	1.0	------	
128	1.5	1.3	------	
127	1.5	.9	------	
126	1.5	1.9	------	
125	1.5	.6	.54	1-4
124	2.0	.5	------	
123	1.5	1.1	------	
122	1.3	.4	------	
121	1.5	.8	------	
120	1.5	.9	.81	
119	1.0	1.5	------	1-5
118	1.0	1.4	------	
117	1.0	.9	------	
116	1.5	1.5	------	
115	1.5	1.5	1.30	
114	1.4	1.2	------	(1-5)
113	1.4	1.3	------	
112	1.6	1.3	------	
111	1.8	.6	------	1-6
110	2.0	1.0	.85	1-7
109	1.2	1.7	------	
108	1.2	1.8	------	
107	1.5	1.7	------	
106	1.5	1.5	------	
105	1.3	1.8	1.77	
104	1.5	1.5	------	
103	1.1	2.1	------	
102	.9	.7	------	1-8
101	.9	.7	------	
100	1.5	.5	.62	
99	1.0	1.9	------	1-9
98	1.0	1.1	------	
97	1.5	1.0	------	
96	1.5	.7	------	
95	1.0	1.9	1.91	
94	1.0	1.7	------	
93	1.0	1.3	------	
92	1.0	1.3	------	
91	1.0	1.3	------	
90	1.0	1.4	1.32	
89	1.0	.9	------	

TABLE 1.—*Radioactivity data and lengths of samples taken from trenches at Morro do Ferro*—Continued

Sample MF-	Length (meters)	Percent $eThO_2$		Composite group
		PdeC	Rio	
Trench 1—Continued				
88	0.8	2.3	------	1–10
87	.9	2.3	------	
86	.8	1.1	------	
85	.8	2.1	2.46	
84	.5	2.1	------	
83	.5	1.7	------	
82	.5	1.4	------	
81	.5	2.3	------	
80	.5	2.1	2.32	
79	.5	1.7	------	
78	.5	1.7	------	
77	.5	1.9	------	
76	.9	.2	------	1–11
75	2.6	.2	.19	
1	1.1	1.2	1.18	1–12
2	.9	1.2	1.30	
3	1.0	1.6	1.57	
4	1.1	1.1	1.17	
5	1.0	2.1	2.05	
6	1.0	1.5	1.50	
7	1.0	1.7	1.63	
8	1.0	1.0	1.02	
9	1.0	1.7	1.67	
10	1.0	1.6	1.69	
11	1.0	1.8	1.87	
12	1.0	.7	.81	
13	1.0	1.6	1.74	
14	1.0	1.8	2.05	
15	.5	.9	.97	
16	.5	2.1	2.09	
17	1.0	1.5	1.38	
18	1.0	.7	.69	1–13
19	1.0	.8	.75	
20	1.0	.6	.65	
21	.9	1.1	1.15	1–14
22	1.0	1.9	1.75	
23	1.0	1.3	1.42	
24	1.0	1.5	1.64	
25	1.0	1.9	2.01	
26	1.0	1.1	1.18	
27	1.0	1.3	1.40	
28	1.0	1.7	1.86	
29	1.0	1.9	1.76	
30	1.0	1.5	1.51	(1–14)
31	1.0	2.1	2.03	
32	1.0	1.4	1.28	
33	1.1	1.2	1.21	
34	.9	2.8	2.93	
35	1.0	2.0	2.04	
36	1.1	1.5	1.88	
37	1.2	2.3	2.19	
38	1.0	.8	.83	1–15
39	1.1	.6	.61	
40	1.5	.8	.75	
41	1.5	.8	.83	
42	1.0	1.3	1.31	
43	1.6	1.0	1.01	
44	1.5	.4	.37	
45	1.6	.8	.87	
46	1.5	.6	.64	
47	1.5	.8	.83	
48	1.5	.6	.62	
49	.8	.6	.68	
50	.7	.9	.91	
51	.8	.6	.68	1–16
52	1.2	.4	.26	
53	1.3	.7	.68	
54	.7	.4	.44	
55	1.0	.5	.66	
56	.9	.7	.79	
57	1.2	.4	.47	
58	1.1	.6	.67	
59	1.6	.4	.43	
60	1.0	.9	.95	
61	1.0	.5	.52	
62	1.2	.4	.33	
63	1.6	.4	.43	
64	1.5	.4	.46	
65	1.5	.5	.52	
66	1.5	.4	.41	
67	1.5	.5	.49	
68	1.5	.5	.50	
69	1.5	.4	.42	
70	.9	.3	.43	
71	1.6	1.4	1.28	1–17
72	.5	.5	.44	
73	1.0	1.7	1.71	
74	.8	1.0	1.11	
Trench 2				
140	1.6	0.6	0.62	2–1
141	1.2	.6	------	
142	.2	.2	------	
143	2.0	0.3	------	(2–1)
144	2.0	.8	------	
145	1.9	.7	.55	

TABLE 1.—*Radioactivity data and lengths of samples taken from trenches at Morro do Ferro*—Continued

Sample MF-	Length (meters)	Percent eThO₂ PdeC	Percent eThO₂ Rio	Composite group	Sample MF-	Length (meters)	Percent eThO₂ PdeC	Percent eThO₂ Rio	Composite group
				Trench 2—Continued					
146	1.5	0.7	------	(2–1)	176	1.7	0.9	------	(2–5)
147	1.5	.9	------		177	.9	1.4	------	
148	2.0	.5	------		178	1.6	.9	------	
149	1.0	.8	------		179	.35	1.2	------	
150	1.0	.7	.65		180	1.25	.9	.68	
					181	1.35	.5	------	
151	1.0	1.0	------	2–2	182	1.85	1.2	------	
152	.6	1.9	------		183	1.3	.9	------	
153	.55	2.6	------		184	1.4	1.0	------	
154	.95	.6	------	2–3	185	1.9	.4	.44	2–6
155	1.8	.3	.23		186	1.95	.4	------	
156	1.4	.3	------		187	1.15	1.3	------	
157	1.2	.3	------		188	2.3	.6	------	
158	.8	.3	------		189	1.9	.6	------	
159	.7	.8	------		190	1.3	.7	.76	
					191	1.9	.6	------	
160	.7	1.4	1.17	2–4	192	1.9	.2	------	
161	1.5	1.6	------		193	2.1	.7	------	
162	1.5	1.5	------		194	1.9	.4	------	
163	1.5	.6	------		195	1.5	.3	.35	
164	1.5	1.9	1.66		196	1.9	.3	------	
165	1.5	1.6	1.28						
166	1.5	2.1	------		197	.7	1.0	------	2–7
167	1.0	1.0	------		198	1.9	.2	------	
168	1.2	1.8	------		199	1.9	.9	------	
169	1.4	.9	------		200	1.9	.4	.43	
170	1.0	.9	.72		201	1.2	.6	------	
					202	1.3	.8	------	
					203	1.8	.4	------	
171	.4	.9	------	2–5	204	2.1	.5	------	
172	1.6	.8	------		205	1.9	.5	.45	
173	1.6	1.0	------		206	2.0	.6	------	
174	1.6	1.1	------		207	1.9	.5	------	
175	.4	1.3	1.69		208	1.9	.5	------	
				Trench 3					
393	1.3	0.7	------	3–1	285	1.7	1.7	1.44	3–3
392	1.6	.7	------		284	1.0	2.5	------	
391	1.2	.8	------		283	.9	1.5	------	
390	.9	1.2	------		282	1.1	1.7	------	
389	1.2	.5	------		281	1.2	1.9	------	
388	1.2	.1	------		280	1.9	1.6	1.47	
387	1.3	.2	------		279	1.2	2.2	1.91	
386	1.2	.2	------		278	1.2	1.6	------	
					277	1.0	1.7	------	
385	1.6	1.0	------	3–2					
384	1.0	1.0	------		276	1.0	1.7	------	3–4
383	1.3	1.3	------		275	.8	1.7	1.69	
382	1.2	1.0	------		274	.7	1.9	------	
381	.6	1.5	------		273	1.6	.9	------	
380	1.8	1.7	------		272	1.7	1.0	------	
288	1.0	1.4	------		271	1.2	1.0	------	
287	1.1	1.4	------		270	.9	1.3	1.27	
286	1.1	1.2	------		269	1.4	1.3	------	

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TABLE 1.—*Radioactivity data and lengths of samples taken from trenches at Morro do Ferro*—Continued

Sample MF-	Length (meters)	Percent $eThO_2$		Composite group	Sample MF-	Length (meters)	Percent $eThO_2$		Composite group
		PdeC	Rio				PdeC	Rio	
Trench 3—Continued									
268	1.3	1.5	------	(3-4)	230	1.3	1.0	0.90	3-9
267	1.4	1.5	------		231	1.6	1.0	------	
					232	1.2	.6	------	
266	1.8	.9	------	3-5	233	.7	1.3	------	
265	2.1	.8	.70		234	1.1	1.7	------	
264	2.1	1.6	------		235	.4	1.5	1.45	
263	1.4	2.3	------		236	.8	2.1	------	
262	1.8	1.9	------		237	.6	2.0	------	
261	1.2	1.5	------		238	.7	1.5	------	
260	.7	1.9	1.78		239	.9	1.4	------	
209	.55	2.1	------		240	.9	2.7	2.88	
210	.7	1.6	1.38		241	.4	1.5	------	
211	1.0	.8	------						
					242	1.2	.7	------	3-10
212	1.7	.5	------	3-6	243	1.4	.6	------	
213	2.0	.3	------		244	1.4	1.0	------	
214	1.15	.5	------		245	.5	.9	.87	
215	.95	.6	.53		246	1.6	.7	------	
216	1.1	.7	------		247	1.3	.4	------	
217	1.7	.6	------		248	1.9	.4	------	
					249	1.5	.2	------	
218	1.65	1.2	------	3-7	250	1.4	.3	.24	
219	.8	1.1	------		251	1.2	.2	------	
220	1.2	1.3	1.16		252	1.9	.4	------	
221	1.5	1.7	------						
222	1.0	1.6	------		253	1.4	.9	------	3-11
223	1.8	.9	------		254	1.3	1.3	------	
					255	1.2	.8	.79	
224	1.8	.5	------	3-8	256	1.3	.8	------	
225	1.8	.5	.67		257	2.3	.5	------	
226	1.9	.5	------		258	1.3	1.1	------	
227	1.7	.5	------		259	2.0	.3	------	
228	2.0	.3	------						
229	.6	.4	------						
Trench 4									
289	1.0	0.3	------	4-1	304	1.1	2.1	------	(4-3)
290	1.6	.2	0.35		305	1.0	1.5	1.48	
291	1.6	.4	------		306	1.1	1.2	------	
292	1.8	.1	------		307	1.5	.9	------	
293	1.8	.2	------		308	.8	1.0	------	
294	1.1	.2	------						
					309	1.6	.5	------	4-4
295	.8	.7	.66	4-2	310	1.9	.3	0.32	
296	1.2	.7	------		311	2.0	.4	------	
297	.8	.8	------		312	1.5	.5	------	
298	.8	.6	------						
299	1.9	.7	------		313	1.6	1.0	------	4-5
300	1.5	1.2	1.20		314	.9	.9	------	
301	1.5	.7	------		315	.9	1.2	1.24	
					316	.9	.6	------	
302	1.7	.9	------	4-3	317	.9	.9	------	
303	.8	2.0	------		318	1.4	1.0	------	

TABLE 1.—*Radioactivity data and lengths of samples taken from trenches at Morro do Ferro*—Continued

Sample MF-	Length (meters)	Percent $eThO_2$		Composite group
		PdeC	Rio	
Trench 4—Continued				
319	1.2	0.9	------	(4–5)
320	.8	.9	.90	
321	1.0	2.0	------	4–6
322	.9	2.2	------	
323	.9	2.0	------	
324	1.3	1.4	------	
325	1.5	2.0	2.06	
326	1.8	1.6	------	
327	1.5	.9	.99	
328	1.7	.9	------	
329	.7	.4	------	4–7
330	2.2	.1	------	
331	2.1	.1	------	
332	1.9	.3	------	
333	1.8	.2	------	
334	1.5	.2	------	
335	2.0	.5	------	4–8
336	1.9	.5	------	
337	1.8	.6	------	
338	1.9	.6	------	
339	1.7	.3	------	
340	1.9	.4	------	
341	2.0	.3	------	
342	1.9	0.1	------	4–9
343	1.7	.1	------	
344	1.7	.1	------	
345	1.8	.1	------	
346	1.6	.1	------	
347	1.0	.1	------	
348	1.3	.4	------	4–10
349	1.4	.7	------	
350	1.9	.7	------	
351	1.6	.7	------	
352	1.8	.5	------	
353	1.7	.7	------	
354	1.8	1.0	------	
355	1.6	1.2	------	
356	1.6	.5	------	
357	1.8	.4	------	4–11
358	1.8	.3	------	
359	1.4	.2	------	
360	2.1	.3	------	
361	1.7	.6	------	
362	1.3	.5	------	
363	1.2	.6	------	
364	1.5	.2	------	4–12
365	2.3	.1	------	
366	2.2	.1	------	
Trench 5				
394	0.6	0.3	------	5–1
395	1.1	.5	------	
396	.8	.7	------	
397	1.0	.9	------	
398	2.0	.6	------	
399	1.2	.5	------	
400	.8	.9	------	5–2
401	.8	1.6	------	
402	1.3	.8	------	
403	1.0	1.0	------	
404	1.2	.6	------	
405	1.0	.9	------	
406	.3	.6	------	
407	.8	.6	------	
408	.4	1.3	------	
409	.6	.3	------	5–3
410	.9	.3	------	
411	1.0	.3	------	
412	1.7	.2	------	
413	1.5	.2	------	
414	1.1	.2	------	
415	1.7	.2	------	
416	1.9	.2	------	
417	2.2	.2	------	
418	2.1	.2	------	
419	1.9	.2	------	
420	2.0	0.2	------	(5–3)
421	1.0	.2	------	
422	2.3	.1	------	5–4
423	2.7	.2	------	
424	1.7	.1	------	
425	1.8	.2	------	
426	2.6	.1	------	
427	3.4	.2	------	
428	2.3	.1	------	
429	2.4	.1	------	
430	2.0	.1	------	
431	.5	.2	------	
432	3.3	.1	------	
433	3.0	.1	------	
434	3.1	.1	------	
435	1.8	.2	------	
436	1.3	.1	------	5–5
437	2.1	.1	------	
438	2.5	.1	------	
439	2.5	.1	------	
440	2.7	.1	------	
441	2.6	.1	------	
442	2.5	.1	------	
443	2.9	.1	------	
444	4.3	.1	------	

To check the radioactivity analyses made in Poços de Caldas, 128 samples of minus 4-mesh size were analyzed a second time in the DNPM–USGS laboratory in Rio de Janeiro. The samples selected for these check analyses were crushed to minus 20-mesh. Their $eThO_2$ content was then determined by comparing their radioactivity with a calibration curve constructed from the radiation measurements of a group of 14 samples that previously had been analyzed chemically for thoria by the USGS in Washington, D.C. (See table 6.) These samples had been collected by G. E. Tolbert (see footnote 1, p. D2) from the earlier DNPM exploration holes. The check analyses are also given in table 1 in the column headed Rio. Because these 128 check analyses were in relatively close agreement with the preliminary analyses made in Poços de Caldas, the remaining horizontal channel samples were not reanalyzed individually.

For convenience in calculating the overall grade of the Morro do Ferro deposit, contiguous trench samples were combined into groups of varied lengths; the combined groups helped to reduce the number of samples to be submitted for chemical analysis. This grouping was such that broad zones of generally high-grade material were separated by significant intervening zones of lower grade material (table 1). The general cutoff grade for distinguishing between the high- and low-grade zones was arbitrarily put at 1.0 percent $eThO_2$. The weighted-average values of both the higher and lower grade zones (table 2) were calculated from the radioactivity analyses made at Poços de Caldas (table 1). Splits of the original samples from the higher grade zones were crushed to minus 20-mesh and then combined on a weighted-volume basis. In each case, the specific volume of the split was directly proportional to the length of each original sample. Portions of each of these composite samples were then crushed to minus 200-mesh and their $eThO_2$ content determined (table 2). Because the differences between these two sets of data, that is, the weighted averages of the composite groups and the analyses of the actual composite samples, did not appear to be significant, the preparation of composite samples for the lower grade zones was deemed unnecessary.

BULK SAMPLE FOR BENEFICIATION TESTS

A bulk sample was taken from the Morro do Ferro ore body by the Cia. Geral de Minas for beneficiation tests. This sample consisted of material scraped from the uphill walls of each trench throughout the lengths of the composite samples (MF–1001 to MF–1019) given in tables 2 and 6. The bulk sample, aggregating several tons of material, was dried, crushed, and split at the company's plant in Poços de Caldas. The data given in the tables of this report under sample MF–BX–1 are from a small split of this bulk sample.

TEST-PIT SAMPLES

As previously indicated the test pits were sampled by channeling the two uphill corners of each pit. These samples, unlike those from the trenches, were taken directly to the DNPM–USGS laboratory in Rio de Janeiro, ground to 20-mesh and assayed for $eThO_2$. The grade variation of the test-pit samples ranged from 0.01 to 2.97 percent $eThO_2$. The sample data are given in table 3.

TABLE 2.—*Equivalent thoria analyses of composite samples and related data of trench samples from Morro do Ferro*

Composite group [1]	Composite sample [2] MF-	Projected length [3] (meters)	Percent $eThO_2$: Weighted average, composite group	Percent $eThO_2$: Composite sample (−200 mesh)
Trench 1				
1–1	----------	2.4	0.25	----------
1–2	----------	4.5	.93	----------
1–3	1001	7.5	1.38	1.52
1–4	----------	6.8	.71	----------
1–5	1002	7.5	1.33	1.42
1–6	----------	1.5	.60	----------
1–7	1003	9.4	1.58	1.41
1–8	----------	2.8	.61	----------
1–9	1004	9.7	1.28	1.41
1–10	1005	6.1	1.91	2.21
1–11	----------	2.8	.20	----------
1–12	1006	15.9	1.47	1.61
1–13	----------	3.0	.70	----------
1–14	1007	16.8	1.68	2.01
1–15	----------	16.4	.76	----------
1–16	----------	21.3	.49	----------
1–17	----------	3.3	1.28	----------
Trench 2				
2–1	----------	15.6	0.64	----------
2–2	1008	1.9	1.64	1.53
2–3	----------	6.6	.39	----------
2–4	1009	14.0	1.42	1.37
2–5	1010	17.0	.93	.99
2–6	----------	21.7	.53	----------
2–7	----------	19.5	.53	----------
Trench 3				
3–1	----------	8.5	0.53	----------
3–2	1011	9.4	1.28	1.13
3–3	1012	9.9	1.80	1.64
3–4	1013	10.6	1.31	1.30
3–5	1014	12.9	1.46	1.24
3–6	----------	8.6	.51	----------
3–7	1015	7.9	1.28	1.27
3–8	----------	9.7	.50	----------
3–9	1016	10.2	1.44	1.47
3–10	----------	14.7	.49	----------
3–11	----------	10.4	.75	----------

See footnotes at end of table.

TABLE 2.—*Equivalent thoria analyses of composite samples and related data of trench samples from Morro do Ferro*—Continued

Composite group [1]	Composite sample [2] MF–	Projected length [3] (meters)	Percent $eThO_2$	
			Weighted average, composite group	Composite sample (–200 mesh)
Trench 4				
4–1	----------	5. 2	0. 23	----------
4–2	----------	4. 9	. 79	----------
4–3	1017	4. 7	1. 30	1. 26
4–4	----------	4. 2	. 42	----------
4–5	1018	5. 0	. 93	1. 00
4–6	1019	6. 2	1. 56	1. 64
4–7	----------	9. 0	. 19	----------
4–8	----------	11. 6	. 44	----------
4–9	----------	8. 4	. 10	----------
4–10	----------	13. 0	. 72	----------
4–11	----------	9. 8	. 41	----------
4–12	----------	5. 3	. 17	----------
Trench 5				
5–1	----------	6. 2	0. 60	----------
5–2	----------	7. 1	. 90	----------
5–3	----------	19. 3	. 21	----------
5–4	----------	29. 1	. 13	----------
5–5	----------	15. 6	. 10	----------

[1] See table 1 for numbers of individual samples included in each composite group.

[2] Mixture of splits from individual samples combined on a weighted-volume basis directly proportional to the length of each original sample.

[3] Length of composite groups adjusted from actual length (table 1) by projection to a line normal to the strike of the main magnetite vein in trench 1 (fig. 3).

GAMMA-RAY LOGGING OF DRILL HOLES

In the gamma-ray logging of the drill holes at Morro do Ferro, difficulties were experienced in calibrating the scintillation-detection equipment, principally because of a lack of adequate sample data from the holes for comparison with the gamma-ray logs. Such data as were available, however, permitted the conversion of the variations shown by the logs into one of five radioactivity levels for every one-half meter of depth. These five levels correspond roughly to the following ranges in equivalent thoria content: less than 0.1; 0.1–0.5; 0.5–1.0; 1.0–1.5; and more than 1.5 percent. The hole-by-hole results of the gamma-ray logging are presented in table 4.

ADIT SAMPLES

Approximately 20 meters of horizontal sampling was done in the company adit at 1,450 meters in the opencut leading to the portal and in the first part of the adit itself (fig. 3). Data on this sampling are

TABLE 3.—*Data on samples from test pits at Morro do Ferro*

[Left and right sides refer, respectively, to left and right uphill corners of pits]

Depth (meters)	Length (meters)	$eThO_2$ (percent)	Depth (meters)	Length (meters)	$eThO_2$ (percent)
Left side			Right side		
Test pit 1					
0 -0. 3	0. 3	1. 25	0 -0. 25	0. 25	1. 16
. 3- . 8	. 5	1. 35	. 25- . 55	. 3	1. 21
. 8-1. 4	. 6	2. 18	. 55-1. 45	. 9	1. 60
1. 4-2. 0	. 6	2. 41	1. 45-1. 95	. 5	2. 02
2. 0-2. 85	. 85	. 98	1. 95-2. 85	. 9	2. 44
2. 85-3. 5	. 65	2. 63	2. 85-3. 35	. 5	. 99
3. 5-3. 9	. 4	2. 97	3. 35-3. 85	. 5	1. 64
Test pit 2					
0 -0. 3	0. 3	0. 92	0 -0. 25	0. 25	0. 75
. 3 - . 8	. 5	1. 50	. 25-1. 0	. 75	1. 00
. 8 -1. 8	1. 0	. 53	1. 0 -1. 6	. 6	. 46
1. 8 -2. 8	1. 0	. 62	1. 6 -2. 6	1. 0	. 30
2. 8 -3. 4	. 6	. 62	2. 6 -3. 3	. 7	. 66
Test pit 3					
0 -0. 5	0. 5	1. 13	0 -0. 5	0. 5	0. 95
. 5 -1. 25	. 75	1. 73	. 5 -1. 25	. 75	2. 07
1. 25-2. 0	. 75	1. 30	1. 25-2. 0	. 75	1. 05
2. 0 -2. 75	. 75	. 45	2. 0 -2. 75	. 75	. 45
2. 75-3. 5	. 75	. 25	2. 75-3. 5	. 75	. 30
3. 5 -5. 0	1. 5	. 15	3. 5 -5. 0	1. 5	. 20
Test pit 4					
0 -0. 45	0. 45	0. 58	0 -0. 15	0. 15	1. 00
. 45-1. 3	. 85	1. 27	. 15- . 7	. 55	1. 58
1. 3 -1. 7	. 4	1. 10	. 7 -1. 3	. 6	. 46
1. 7 -2. 2	. 5	. 05	1. 3 -1. 8	. 5	. 01
2. 2 -3. 0	. 8	. 04	1. 8 -2. 6	. 8	. 04
3. 0 -4. 0	1. 0	. 01	2. 6 -3. 5	. 9	. 04

given in table 5. This sampling extended to a point where the adit dog-legged to crosscut the 1 percent $eThO_2$ area outlined from the trenching (fig. 3). Although caving in the inner part of the adit prevented further sampling, a hasty scintillation counter traverse made just prior to the abandonment of the adit indicated no material that exceeds 0.1 percent $eThO_2$.

Although no systematic sampling of the DNPM adit at 1,480 meters (fig. 3) was attempted, four grab samples were obtained along the trend of the main magnetite vein on its hanging-wall side. These samples represented relative highs and lows in radioactivity.

TABLE 4.—*Results of gamma-ray logging of selected drill holes at Morro do Ferro*

[Levels of radioactivity indicated by the symbols I, II, III, IIII, and IIIII correspond roughly to <0.1, 0.1–0.5, 0.5–1.0, 1.0–1.5, and >1.5 percent $eThO_2$, respectively]

Hole	Depth (meters)	Radioactivity level
A	0 – ½	III
	½ – 2	II
	2 – 2½	III
	2½ – 4½	II
	4½ – 7	III
	7 – 7½	II
	7½ – 8½	IIII
	8½ – 9½	III
	9½ – 11	II
B	0 – ½	II
	½ – 1½	III
	1½ – 5	II
	5 – 6½	III
	6½ – 9	II
C	0 – 10	II
D	0 – 11	II
E	0 – 2	III
	2 – 10	II
	10 – 12	III
	12 – 14	II
F	0 – 2	III
	2 – 4	IIII
	4 – 5	III
	5 – 6	II
	6 – 7	III
	7 – 10½	II
G	0 – ½	II
	½ – 3½	III
	3½ – 6	II
H	0 – 1	IIII
	1 – 3	IIIII
	3 – 4	III
	4 – 6	IIII
	6 – 7	III
I	0 – 1	III
	1 – 2	IIIII
J	0 – 4	III
	4 – 6	IIII
	6 – 8½	III
K	0 – 8½	II
	8½ – 10	III
	10 – 19	II
	19 – 20	IIII
	20 – 25	II
	25 – 26½	III
	26½ – 28	IIII
	28 – 29	III
	29 – 47	II
	47 – 49	III
	49 – 53	II
L	0 – 2½	III
	2½ – 6½	II
	6½ – 9	III
M	0 – 2	II
	2 – 9	I
N	0 – 1½	IIII
	1½ – 2½	IIIII
	2½ – 5	IIII
	5 – 8	IIIII
	8 – 10½	IIII
O	0 – 3½	IIIII
P	0 – 3½	IIII
	3½ – 7	III
	11 – 11	IIII
Q	0 – 3	III
	3 – 4½	IIII
	4½ – 8	III
	8 – 9	IIII
	9 – 11	III
R	0 – 1	IIII
	1 – 5	IIIII
	5 – 6	III
	6 – 9½	IIII
S	0 – 3	IIII
	3 – 6½	III
	6½ – 8½	IIII
T	0 – 13	II
	13 – 15	I
	15 – 19	II
	19 – 27	I
	27 – 29	II
	29 – 31	I
	31 – 32	II
	32 – 41	I
	41 – 45	II
	45 – 47	I
U	0 – 1	II
	1 – 3½	III
V	0 – ½	II
	½ – 1	III
	1 – 7	II
	7 – 7½	III
	7½ – 9½	II
W	0 – ½	IIII
	½ – 1	IIIII
	1 – 3½	IIII
	3½ – 13	III
	13 – 14	II
	14 – 15	III
X	0 – 1	III
	1 – 2½	II
	2½ – 3	III
	3 – 6½	II
	6½ – 7½	III
	7½ – 8	IIII
	8 – 9	II
Y	0 – 1½	IIIII
	1½ – 2	IIII
	2 – 3	III
	3 – 5½	II
Z	0 – 2	III
	2 – 3	IIII
	3 – 4	III
AA	0 – 1	III
	1 – 2½	IIII
AB	0 – 3	II

TABLE 4.—*Results of gamma-ray logging of selected drill holes at Morro do Ferro*—Continued

Hole	Depth (meters)	Radioactivity level	Hole	Depth (meters)	Radioactivity level
	3 -10	I		3 - 4	I
	10 -11½	II		4 - 5	II
AD	0 - 1	III		5 - 5½	I
	1 - 3	IIIII	AG	0 - 6	II
	3 - 5	IIII	AH	0 - 1½	II
	5 - 6	III		1½ - 9	I
	6 -. 7½	II	AI	0 - 1	IIII
AE	0 - 3	II		1 - 2	III
	3 - 5	I		2 - 8	II
	5 - 6½	II	AJ	0 - 1½	II
	6½ - 7	III		1½ -10	I
	7 - 7½	IIII	AK	0 - 1	II
	7½ - 9½	III		1 - 2	III
	9½ -10½	I		2 - 4	II
AF	0 - 3	II		4 - 6½	I

TABLE 5.—*Data on samples taken from the Cia. Geral de Minas adit at 1,450 meters on Morro do Ferro*

Distance from entrance of cut [1] (meters)	Sample length (meters)	$eThO_2$ (percent)	Approximate mean depth of sample below surface (meters)
0- 1. 7	Not sampled, ground disturbed.		
1. 7- 2. 7	1. 0	0. 27	2
2. 7- 4. 6	1. 9	. 13	3
4. 6- 6. 4	1. 8	. 10	3½
6. 4- 8. 0	1. 6	. 14	4
8. 0- 9. 8	1. 8	. 10	5
9. 8-12. 0	2. 2	. 11	5½
12. 0-14. 0	2. 0	. 08	6½
14. 0-16. 0	2. 0	. 09	7
16. 0-18. 0	2. 0	. 08	7½
18. 0-19. 5	1. 5	. 08	8
19. 5-20. 4	. 9	. 05	8

[1] Portal of adit at 9.8 meters. Samples taken from 1.7 to 9.8 meters were from wall of opencut leading to portal of adit; those from 9.8 to 20.4 meters were from wall of adit.

The radioactivity of these samples is erratic as shown in the table below; percent $eThO_2$ and the relative position of these four samples follows:

Sample MF-	*Approximate distance from portal (meters)*	*Approximate depth below surface (meters)*	$eThO_2$ *(percent)*
445	25	13	2. 50
446	64	26	. 90
10G	100	35	2. 56
11G	110	36	. 78

CHEMICAL ANALYSES

The data on all available samples from Morro do Ferro that were analyzed chemically are given in table 6.

TABLE 6.—*Chemical and radioactivity analyses, in percent, and related data of selected samples from Morro do Ferro*

[TREO=total rare-earth oxides]

Sample	TREO+ ThO_2 [1]	TREO [2]	ThO_2	$eThO_2$	U_3O_8	Depth (meters)	TREO: $eThO_2$
Drill-hole samples							
DNPM- 1	2. 22	2. 09	0. 13	0. 17	0. 009	10. 6–11	10. 5
4	9. 61	8. 82	. 79	. 71	. 004	4–5	11. 6
5	2. 89	2. 04	. 85	. 95	. 005	11–12	2. 0
7	9. 52	8. 47	1. 05	1. 31	. 002	1–2	6. 5
10	10. 93	9. 46	1. 47	1. 68	. 006	1–2	5. 6
12	11. 21	9. 09	2. 12	2. 15	. 002	7–8	4. 1
13	22. 39	19. 82	2. 59	2. 53	. 007	1–2	7. 9
14	22. 68	19. 89	2. 79	2. 79	. 007	3–4	7. 1
15	2. 02	1. 73	0. 29	0. 37	. 005	1–2	4. 2
16	9. 74	9. 05	0. 69	0. 63	. 015	4–6	15. 0
17	13. 75	12. 16	1. 59	1. 10	. 013	4–5	11. 1
18	22. 66	21. 13	1. 53	1. 27	. 019	1–2	16. 2
19	21. 66	19. 95	1. 71	1. 71	. 021	3–4	11. 8
20	8. 48	7. 35	1. 13	1. 29	. 006	1–1. 6	5. 7
Trench samples							
MF- 3	12. 48	10. 9	1. 58	1. 54	0. 026		7. 3
8	4. 76	3. 6	1. 16	1. 00	. 012		3. 6
25	17. 06	14. 8	2. 26	1. 96	. 024		7. 4
34	10. 77	7. 0	3. 77	2. 93	. 012		2. 4
44	1. 98	1. 5	. 48	0. 42	. 004		3. 8
133	7. 00	5. 74		1. 26			4. 4
164	5. 14	3. 62		1. 52			2. 4
279	7. 42	5. 63		1. 79			3. 1
327	7. 77	6. 73		1. 04			6. 7
374	11. 55	8. 07		3. 48			2. 3
1001	8. 91	7. 39		1. 52			4. 9
1002	10. 82	9. 40	1. 58	1. 42	. 007		6. 7
1003	11. 87	10. 46		1. 41			7. 5
1004	9. 61	8. 20		1. 41			5. 9
1005	10. 57	8. 36	2. 65	2. 21	. 007		3. 8
1006	7. 57	5. 96		1. 61			3. 8
1007	8. 20	6. 19		2. 01			3. 1
1008	9. 69	8. 16		1. 53			5. 5
1009	4. 80	3. 43	1. 58	1. 37	. 006		2. 4
1010	5. 25	4. 26		0. 99			4. 3
1011	5. 51	4. 38		1. 13			4. 0
1012	6. 76	5. 12		1. 64			3. 2
1013	3. 66	2. 36		1. 30			1. 8
1014	3. 49	2. 25	1. 40	1. 24	. 005		1. 8
1015	2. 71	1. 44		1. 27			1. 1
1016	2. 70	1. 23		1. 47			0. 8
1017	4. 69	3. 43		1. 26			2. 6
1018	4. 86	3. 86		1. 00			3. 9
1019	10. 72	9. 08	1. 70	1. 64	. 011		5. 7
1020 [3]	5. 95	4. 65		1. 30			3. 6
BX-1 [4]	7. 05	5. 79	1. 26	1. 25	. 002	0–2	4. 6
WA [5]	8. 13	6. 69		1. 44			4. 6

[1] TREO+ThO^2 calculated from separate chemical analyses of TREO and ThO_2 for DNPM samples, samples MF-3, -8, -25, -34, and -44, and sample MF-BX-1.

[2] TREO calculated [(TREO+ThO_2)−$eThO_2$] for samples MF-133, -164, -279, -327, -374, and -1001 through -1020.

[3] Sample MF-1020 is a composite sample prepared by mixing splits of samples MF-1001 through -1019 on a weighted-volume basis.

[4] Sample MF-BX-1 is a small split of a bulk sample taken for benefication tests and represents about the same part of the ore body as sample MF-1020.

[5] WA, average (weighted by projected sample length) of composite group samples MF-1001 through -1019.

THORIA

Because of the close correlation between thoria and equivalent thoria shown in the 14 DNPM drill-hole samples analyzed as standards (see table 6), only 10 trench samples were analyzed chemically for thoria. Of these samples, 5 were from among the first 50 samples (MF–1 through –50, table 1) taken from trench 1, and 5 more were selected from the 19 composite group samples (table 2). The $eThO_2$ and ThO_2 values determined for these 10 samples can be compared in table 6 (samples MF–3, –8, –25, –34, –44, –1002, –1005, –1009, –1014, and –1019). In these samples all thoria values are slightly higher than the equivalent thoria values. The deviations (that is, ThO_2 minus $eThO_2$) range from +0.04 to +0.84 with an average of +0.24 percent. These differences between thoria and equivalent thoria values were not considered significant; hence, the equivalent thoria data were not increased correspondingly for the calculation of the overall thoria grade of the deposit.

TOTAL RARE-EARTH OXIDES

The 19 composite group samples (samples MF–1001 through –1019, table 6) were analyzed chemically for total rare-earth oxides plus thoria ($TREO+ThO_2$) at the DNPM laboratory in Rio de Janeiro. The TREO content of each of these samples was then computed by subtracting the respective equivalent thoria values. A check on the reliability of this method of obtaining the TREO values was made by submitting duplicates of five of these samples simultaneously to the U.S. Geological Survey in Washington, D.C., and to the Instituto de Pesquizas Tecnológicas in São Paulo for separate determinations of thoria and total rare-earth oxides. The results of the analyses from the three laboratories, rounded to the nearest 0.1 percent, are given in table 7; because they were so close, it is assumed that the procedure for calculating the TREO content of the Morro do Ferro samples by subtracting $eThO_2$ from the $TREO+ThO_2$ chemical analyses is sufficiently accurate for the purpose of this report.

Other samples analyzed for total rare-earth oxides excluding ThO_2 were the 14 DNPM drill-hole samples, originally run for thoria standards, and the 5 individual trench samples (MF–3, –8, –25, –34, and –44). Individual trench samples analyzed for $TREO+ThO_2$ were MF–133, –164, –279, –327, and –374. (See table 6.)

URANIUM

Twenty-four samples from Morro do Ferro were analyzed chemically for uranium or uranium oxide. The uranium content of these samples, recalculated where necessary to percent U_3O_8, is given in table 6.

TABLE 7.—*Comparison of analyses of five selected composite group samples from Morro do Ferro*

Sample MF-	USGS [1]	DNPM [2]	IPT [3]
Total rare-earth oxides plus thoria			
1002	11. 0	10. 8	11. 1
1005	11. 1	10. 6	10. 8
1009	4. 6	4. 8	4. 8
1014	3. 8	3. 5	3. 5
1019	11. 5	10. 7	11. 5
Total rare-earth oxides			
1002	9. 4	9. 4	9. 5
1005	8. 5	8. 4	8. 2
1009	3. 0	3. 4	2. 9
1014	2. 4	2. 3	2. 0
1019	9. 8	9. 1	9. 9
Thoria [4]			
1002	1. 6	1. 4	1. 6
1005	2. 6	2. 2	2. 6
1009	1. 6	1. 4	1. 8
1014	1. 4	1. 2	1. 6
1019	1. 7	1. 6	1. 6

[1] U.S Geological Survey, Washington, D.C. Analysts: B. Ingram, L. Jenkins, H Kramer, and R. Moore.
[2] Departamento Nacional da Produção Mineral, Rio de Janeiro, D.F. Analyst: Carlos Pires Ferreira.
[3] Instituto de Pesquizas Tecnológicas, São Paulo, S.P. Enalyst: João Ricotti Pucci.
[4] Thoria values are by chemical methods for USGS and IPT and by radiometric methods for DNPM.

SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSES

The five individual trench samples (MF–3, –8, –25, –34, and –44) that were analyzed chemically for thoria and total rare-earth oxides (table 6) were also analyzed semiquantitatively by spectrographic methods in the U.S. Geological Survey. The results are given in table 8. Yttrium and all the lanthanide elements except promethium, terbium, holmium, thulium, and lutetium were identified in one or more of the samples tested. The extreme abundance of the cerium earths relative to the yttrium earths is notable. The low silicon values (1–5 percent) in all samples attest to the laterization of the parent alkalic rock.

THORIUM AND RARE-EARTH MINERALS

Almost all of the bedrock at Morro do Ferro has been altered to a compact clayey laterite by deep weathering. As the depth of this laterite probably exceeds 100 meters, all the available material for mineralogic study, except for the magnetite of the stockwork veins,

TABLE 8.—*Semiquantitative spectrographic analyses of five samples from Morro do Ferro*

[Analyst: Mona Frank, U.S. Geol. Survey. Sample number is designated by MF. Laboratory number is in parentheses]

Weight percent	Elements				
	MF-3 (144512)	MF-8 (144513)	MF-25 (144514)	MF-34 (144515)	MF-44 (144516)
More than 10	Fe	Fe	Fe	Al	Fe
5-10	Ce, Al	Al	Ce, Al	Fe	Al
1-5	Th, La, Si	Si, Ce, K	La, Si, K, Th	Si, Th, K	Si, K
0.5-1	Nd, K, Ti	Mn, Th, Ti	Mn, Nd	Ce, La, Ti Mn	Ti
0.1-0.5	Mn, Y, Pr, V, Ca	La, Nd, Ba, Ca	Ti, Pr, V, Y, Ca	Nd, Y, Ca	Mg, La, Nd, Th, V, Mn
0.05-0.1	Sr, Zr, Ba	V, Zr, Y, Sr	Sr, Zr, Ba	V, Zr, Sr, P, Mg, Pr	Zr, Ce, Sr, Ca
0.01-0.05	Sc, Gd, Nb, Pb, Er, Mg, Mo, B, Dy, Eu	Nb, Pb, Mg, Mo, Pr, B, Eu, Gd	Sc, Gd, Mg, Nb, B, Dy, Er	Pb, Nb, Ba, Eu, Gd, Er, Sc, B, Dy	Y, Pr, Ba, B, Nb
0.005-0.01	Yb, Ga, Sm	Ga, Sm, Yb, Dy, Er	Yb, Ga, Sm, Mo, Eu, Pb	Yb, Ga, Sm, Mo	Ga, Er, Pb, Dy
0.001-0.005	Cu, Co, Cr	Co, Sc, Cu, Cr	Cu, Co	Sn, Cu	Yb, Mo, Cr, Sc, Sn, Cu
0.0005-0.001	----	----	Cr	Cr	----
0.0001-0.0005	Be, Ag	Ag, Be	Ag, Be	Be, Ag	Be, Ag

has been altered to some extent by the weathering processes. Feldspar phenocrysts of the original porphyritic syenite are completely kaolinized, and much of the groundmass now consists of intermixed kaolin and hydromica. Gibbsite and limonite are readily apparent constituents of some samples. In other samples some of the magnetite has been oxidized to hematite.

Among the rare-earth- and thorium-bearing minerals so far identified from Morro do Ferro, the first to be recognized was bastnaesite. It was identified in 1954 by C. J. Spengler, Jerome Stone, and D. D. Riska of the U.S. Geological Survey (written commun., 1954). In 1956, Elisiario Tavora of the Brazilian Department of Mines (DNPM) identified thorogummite and allanite and verified the occurrence of bastnaesite (written commun., 1955). More recently, Frondel and Marvin (1959) reported the presence of cerianite (CeO_2) in some yellowish-green material taken from the Morro do Ferro trenches. Cerianite in the natural state had been known previously only from the Sudbury district of Ontario, where it occurs in association with a carbonate dike in nepheline syenite (Graham, 1955). In 1955 Elisiario Tavora (written commun., 1955) identified cerium oxide by X-ray analysis of several samples from Morro do Ferro, but the significance of this identification was not appreciated by the author until the work of Frondel and Marvin on cerianite was published.

In the samples from Morro do Ferro examined by the author, the bastnaesite was found chiefly as small botryoidal or mammillary masses that readily disintegrated to a fine powdery material. The thorogummite generally appears as tiny irregular, conchoidally fractured, waxy fragments that are colorless, white, brick red or black; two or more of these colors were common in the same fragment. Allanite is typically black and vitreous and was observed only as tiny grains at the centers of several reddish or yellowish, porous, powdery, claylike aggregates. These claylike aggregates are apparently the weathered alteration product of allanite and resemble the descriptions of the weathering products derived from allanites in certain Virginia pegmatites (Watson, 1917). The cerianite is also generally very fine grained and, where present in significant amounts, imparts a yellowish-green tinge to the clay and decomposed rock masses.

Allanite is most likely the major rare-earth-bearing radioactive material in the primary ore deposit at Morro do Ferro. The bastnaesite, cerianite, and thorogummite are the major recognizable alteration minerals derived from the laterization of the allanite (Wedow, 1961b). Doubtless other oxides, fluorocarbonates, and hydrous silicates containing the rare-earth elements and thorium will be identified by more detailed mineralogic studies.

RELATION OF RARE-EARTH ELEMENTS TO THORIUM

The scatter diagram of figure 4 shows graphically the relation of total rare-earth oxides (TREO) to equivalent thoria ($eThO_2$) in the samples given in table 6. Equivalent thoria has been used for comparison with total rare-earth oxides because the radiometric values were available for all the samples given whereas chemical values were not. Study of the diagram shows that, in spite of a broad general correlation between TREO and $eThO_2$, individual samples of relatively small lateral or vertical extent have a much broader scatter than the composite trench samples that are of much greater linear extent. Regression analysis of the data set and subsets in figure 4 shows that the relation between the rare-earth elements and thorium is not particularly consistent and that variation in this relation, expressed, for example, by the ratio TREO: $eThO_2$, might be due to the interaction of the various geologic processes operative on the deposit during and after its emplacement. The TREO: $eThO_2$ ratios were calculated from the data in table 6, after the pertinent analyses were rounded to the nearest 0.1 percent. The ratios themselves were also rounded to the nearest tenth and given in table 6.

Several summary statistics, specifically the range, spread, and median, of the total set and selected subsets of the ratios are given in table 9. Comparisons among the subsets of these ratios show significant differences that probably depend on the position of the sample within the deposit and the types of material included in the sample. For example, the first 8 of the 14 DNPM drill-hole samples originally selected for use as radioactivity standards were labeled

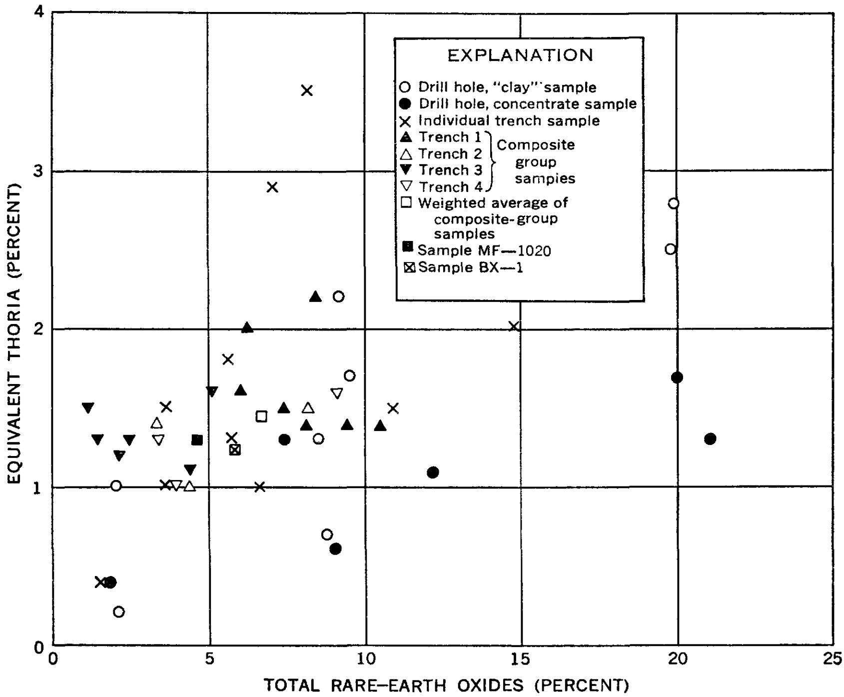

FIGURE 4.—Scatter diagram of paired total rare-earth oxide and equivalent thoria analyses of selected samples from Morro do Ferro.

"clay" and presumably represent unconcentrated material. These "clay" samples, as shown in table 9, have a different range, spread, and median value than the other six drill-hole samples which had been panned in an attempt to concentrate the radioactive minerals. The much higher median TREO:$eThO_2$ ratio for the concentrates suggests that more thorium than rare-earth elements may be in the finer or lighter particles. Consequently, in the panning process more thorium was removed or at least not significantly concentrated, relative to the rare earths. Comparison of the 10 unconcentrated individual trench samples with the drill-hole data further emphasizes the differences between the concentrated and unconcentrated material.

Ordering of the TREO:$eThO_2$ ratios of the 19 composite trench samples (table 6) in subsets by trench (table 9) shows that the trenches have virtually the same spread of ratios but different median values and ranges. The ratios of trench 1 suggest greater concentrations of TREO, relative to the radioactivity, in the surficial materials at the broadest part of the ore body. The extremely low median ratio and range for trench 3 indicates an impoverishment of TREO relative to $eThO_2$ in this area of the ore body because the level of radioactivity

TABLE 9.—*Selected statistics of TREO:*$eThO_2$ *ratios in samples from Morro do Ferro (from data in table 6)*

Sample groups	Number	TREO:$eThO_2$ ratios		
		Range	Spread	Median
All samples [1]	43	0. 8–16. 2	15. 4	4. 3
Individual trench and drill-hole samples	24	2. 0–16. 2	14. 2	6. 9
Individual trench samples	10	2. 3– 7. 4	5. 1	3. 7
Individual drill-hole samples	14	2. 0–16. 2	14. 2	7. 2
"Clay" samples	8	2. 0–11. 6	9. 6	6. 8
"Concentrate" samples	6	4. 2–16. 2	12. 0	11. 4
Composite trench samples	19	. 8– 7. 5	6. 7	3. 8
Trench 1	7	3. 1– 7. 5	3. 4	4. 9
Trench 2	3	2. 4– 5. 5	3. 1	4. 3
Trench 3	6	. 8– 4. 0	3. 2	1. 8
Trench 4	3	2. 6– 5. 7	3. 1	3. 9
All composite samples NE. of main dike	6	. 8– 4. 3	3. 5	2. 8
All composite samples SW. of main dike	13	1. 8– 7. 5	5. 7	4. 0
Sample MF–1020	1			3. 6
Sample MF–BX–1	1			4. 6

[1] Except MF-1020 and MF-BX-1.

is virtually the same as in trench 1. The similarity of all three statistics of the composite samples from trenches 2 and 4 suggests that in the tapering ends of the ore body concentrations of TREO relative to $eThO_2$ are intermediate to those shown by trenches 1 and 3. The ratios of the composite trench samples were next reordered into two subsets relative to position northeast or southwest of the main magnetite dike (fig. 3). The statistics of these arrays show that comparable levels of high radioactivity in the trenches are relatively enriched in the rare earths to the southwest of the main dike or relatively impoverished on the northeast side.

Causes of the variations in the relative concentrations of the rare earths and thorium, however, cannot by judged from the information now at hand. Such causes arise from: the initial variations in the primary deposit, whatever its origin; and redistribution of these elements by later hydrothermal solutions and by laterization and erosion as mentioned above. In addition, the above factors must all be considered with respect to such controlling structural features as the joint systems in the original country rock and the veins and dikes of the magnetite stockwork.

The collection and preparation of the samples for analysis, that is, channel sampling followed by crushing of the material to minus 20-mesh, may also be a factor that will cause some variation in the TREO:$eThO_2$ ratios. Such treatment of the highly weathered Morro do Ferro material could tend to produce a greater proportion of the finer grain sizes from the more brittle and powdery minerals than from the tougher ones. Subsequent handling of these samples may then cause shifts in the TREO:$eThO_2$ ratios by the loss of the finer grain sizes through an inadvertent sifting or winnowing process. The increase in TREO over $eThO_2$ by washing (panning) has already been indicated in the comparison of the two types of DNPM drill-hole samples (table 9).

GRADE AND SIZE OF THE DEPOSIT

Radiometric analyses supplemented by data from surface traversing with radiation-detection equipment and the gamma-ray logging of drill holes indicate the occurrence of a large body of radioactive material at Morro do Ferro, much of which contains 1.0 percent or more $eThO_2$. More than 500 samples were analyzed radiometrically. Because the chemical analyses of selected samples show relatively little uranium compared to thorium (table 6), the radiometric analyses have been calculated as percent equivalent thoria ($eThO_2$).

The near-surface part of the deposit including almost all the material containing 1.0 or more percent $eThO_2$ is roughly lenticular in plan (fig. 3). This area has an overall horizontal length of about 500 meters. It tapers from a maximum width of about 130 meters near trench 1 northwestward to about 5 meters in trench 5 and southwestward to about 20 meters in trench 4. Further study of the radiometric data shows that about 50 percent of the near-surface material in the central area contains 1.0 or more percent $eThO_2$ and the average of all this shallow material is close to 1 percent. Outward from the higher grade zone the radioactivity declines rapidly, although there is generally a halo as much as several tens of meters broad that contains considerable material ranging from 0.5 to 1.0 percent $eThO_2$.

The decline of the radioactivity with depth seems to indicate that the higher grade material is confined to the upper 15 meters of the central zone; below this depth such material becomes spotty and pockety and mostly low-grade material is found.

Specific overall $eThO_2$ grade calculations of the near-surface material in the central zone and its surrounding halo were calculated using various data sets. The weighted-average grade of the central zone, as calculated from the original trench-sample data (tables 1, 2), is 1.14 percent $eThO_2$. When composite trench sample analyses are substituted where available (table 2), this average changes only to 1.16 percent $eThO_2$. Similar weighted averages of only the higher grade zones in the trenches within the central area are 1.39 and 1.44 percent $eThO_2$, respectively. A weighted-volume composite sample (MF-1020, table 6) and the large beneficiation sample (MF-BX-1, table 6), also representing the higher grade zones of the central area, assayed 1.30 and 1.25 percent $eThO_2$ respectively. and thus are closely comparable to the weighted averages of similar material given previously. The weighted-average grade of the near-surface part of the surrounding less-radioactive halo, using the data of selected trench samples, is calculated as 0.57 percent $eThO_2$.

Calculations with the meager data afforded by the gamma-ray logs of the drill holes show that the average grade of 5-meter depth intervals in the central zone are 0.97, 0.81, and 0.63 percent $eThO_2$ respectively, for successive depths of 0–5, 5–10, and 10–15 meters. These data also show an average of 1.17 percent $eThO_2$ for the depth range of 1–2 meters, a value closely comparable to the averages for the trenches. In the halo area to a depth of about 15 meters, the drill-hole samples contained an average of 0.4–0.5 percent $eThO_2$.

The chemical analyses of the higher grade material from the trenches in the central lenticular zone show a weighted average of combined total rare-earth oxides and thoria as 8.13 percent. If the weighted average equivalent thoria (1.44 percent) is assumed to be thoria then the average total rare-earth oxide content is 6.69 percent (table 6). The TREO:ThO_2 ratio, 4.6, calculated from these average values, is used for estimating the average total rare-earth oxide content of the material at Morro do Ferro.

The area of the central lenticular zone of the Morro do Ferro deposit is about 37,000 square meters. The surrounding lower grade halo has an area estimated at about 25,000 square meters. Because the specific gravity of this ore is highly variable as it depends chiefly upon the amount of included iron oxides, the average conversion factor for tonnage calculations has been estimated conservatively at 2.5 metric tons per cubic meter. Tonnages based on these data then amount to about 90,000 and 60,000 metric tons per meter of depth for the central and halo areas, respectively.

The Morro do Ferro deposit is estimated, therefore, to contain over a million and a half metric tons of readily available material at depths not exceeding 15 meters. Two-thirds of this tonnage will be in a central richer zone that will average close to 1 percent thoria and 4 percent total rare-earth oxides; the remainder will be in a lower grade halo averaging close to ½ percent thoria and 1½–2½ percent total rare-earth oxides.

BENEFICIATION TESTS

In the attempt to segregate the thorium and rare-earth minerals for identification, 10 samples representing possible different lithologic types, variations in grade, and positions within the deposit were separated into numerous fractions and subfractions by several methods of concentration. After some experimental work, a routine treatment for all the samples was selected. In addition to the 10 samples mentioned above, a split of the large sample (MF–BX–1), taken by the Cia. Geral de Minas for private beneficiation tests, was fractionated by the same routine. Compilation of the data on these sample fractions gives some measure of the problems to be met in beneficiating the Morro do Ferro ore. The steps taken in this mineralogical concentration routine are given below.

1. Grinding to minus 20-mesh size of a split from field sample.
2. Agitation of 100–500 grams of sample from Step 1 in water until particles appeared dispersed (time of agitation generally 5–10 minutes).
3. Decantation of material in suspension in Step 2 after allowing about a 2-minute settling period.
4. Drying and screening through 80-, 140-, and 200-mesh sieves of material remaining after decantation of fines in Step 3.
5. Separation with bromoform (specific gravity about 2.8) of plus 80-mesh (minus 20-mesh) material from Step 4 into light and heavy fractions.
6. Removal of highly magnetic material from heavier-than-bromoform fraction of Step 5 with Alnico hand magnet.
7. Separation of remaining material from Step 6 into 0.1-, 0.3-, 0.5-, and 0.7-ampere paramagnetic fractions and an essentially nonmagnetic residue with a Frantz isodynamic separator.

After each step of the separation procedure, the $eThO_2$ content of the resulting fractions was determined. The percentage by weight of each fraction relative to the total weight of the selected split from the field sample (Step 1 of procedure) was also calculated. These data are given in table 10. The variability of the data indicates that although the methods used (sizing, gravity, and magnetic concentration) can aid in isolating the radioactive and rare-earth minerals for identification, the application of such methods alone would not be sufficient to provide economic beneficiation of the Morro do Ferro ores.

The causes for all the variations in the radioactivity of the fractions resulting from the attempt to isolate the radioactive and rare-earth minerals are not yet clearly understood. The radioactive material remaining in the fines after washing and screening are such minerals as bastnaesite, cerianite, thorogummite, and the highly altered allanite all of which powder readily during crushing or which occur originally in a more finely divided state. That most of the radioactive minerals have a relatively high specific gravity is shown by their tendency to concentrate in the heavier-than-bromoform fraction. The radioactivity of the plus 80-mesh lighter-than-bromoform fraction is ascribed to the fact that fine-grained heavier particles of the radio-

TABLE 10.—*Equivalent thoria content of selected size, specific*

OS: Original sample (minus 20-mesh).
FW: Fine-wash material recovered from decantation in Step 3.
CW: Coarse-wash material remaining after decantation of suspended fines in Step 3.
−200: Minus 200-mesh material from Step 4.
+200: Plus 200-mesh (minus 140-mesh) material from Step 4.
+140: Plus 140-mesh (minus 80-mesh) material from Step 4.
+80: Plus 80-mesh (minus 20-mesh) material from Step 4.
BL: Lighter-than-bromoform material from Step 5.

[Upper number for each entry is percent equivalent thoria

Sample	Location and type	Description	OS
MF- 25	Trench 1; 23.0–24.0 meters NE. of main magnetite dike; 1.0 meter long horizontal channel at base of trench.	Reddish-brown iron-stained decomposed rock with few magnetite veinlets.	2.07 *100*
279	Trench 3; 28.2–29.4 meters NE. of SW. end of trench; 1.2 meter long horizontal channel at base of trench.	Dark-reddish-brown heavily iron stained decomposed rock with numerous magnetite veinlets.	1.95 *100*
75	Trench 1; 2.6 meters long horizontal chip sample across part of main magnetite dike.	Chiefly fresh black magnetite rock.	0.19 *100*
379	Trench 1; vertical channel in uphill face of trench 32.5 meters NE. of main magnetite dike sample is 0.2 meters long from 0.0–0.2 meters of depth.	Eluvial concentration of magnetite and other rock at surface ("canga").	1.00 *100*
374	Trench 1; same vertical channel as sample MF-379, but from depth of 0.30–0.42 meters below surface.	Highly bleached white to tan to yellow decomposed rock.	3.73 *100*
801	Vicinity of trench 4; grab sample of float rock.	Decomposed float material showing strong yellow-green color suggestive of high rare-earth mineral content.	1.06 *100*
445	DNPM adit; grab sample 25± meters from portal.	Brown decomposed rock; may have been coarse grained originally.	2.50 *100*
446	DNPM adit; grab sample 64± meters from portal.	Light-yellow to tan decomposed rock.	0.90 *100*
BX- 1	Small split of composite sample taken by Cia. Geral de Minas for ore dressing tests.		1.25 *100*
10G	DNPM adit; grab sample 100± meters from portal.	Brownish decomposed rock.	2.56 *100*
11G	DNPM adit; grab sample 110± meters from portal.	Brownish decomposed rock.	0.78 *100*
Average of all above samples except MF-BX-1			1.67 *100*

active minerals were buoyed up by the lighter porous claylike aggregates. In the fractions of decreasing magnetic susceptibility, the causes for the variations in radioactivity are exceedingly complex because of mineralogic variability. Generally, the allanite, where fresh, is nonmagnetic at 0.1 ampere but magnetic at 0.3 ampere. As the allanite becomes altered to a powdery claylike aggregate, or as the quantity of allanite in such an aggregate decreases, these aggregates have decreasing magnetic susceptibility.

The radioactivity of at least part of the material in the nonmagnetic fraction after separation at 0.7 ampere on the Frantz separator is considered to be caused by uranium. Chemical analysis of this fraction of sample MF–BX–1 showed 0.056 percent U_3O_8, a considerable concentration of uranium over the 0.002 percent U_3O_8 obtained in the analysis of the original sample. It is believed that the uranium occurs chiefly in zircon, which, in contrast to the other radioactive minerals identified, is concentrated only in the least magnetic fraction. Thus, the variation in the trace amounts of uranium in the samples analyzed *gravity, and magnetic fractions of 11 samples from Morro do Ferro*

BH: Heavier-than-bromoform material from Step 5.
HM: Highly magnetic material from BH-fraction in Step 6.
0.1, 0.3, 0.5, 0.7: Magnetic fractions (in amperes) obtained by separation with Frantz isodynamic separator in Step 7.
0.7N: 0.7 ampere nonmagnetic fraction remaining in Step 7.

($eThO_2$). Italic number is percent of total sample in fraction]

FW	CW	−200	+200	+140	+80	BL	BH	HM	0.1	0.3	0.5	0.7	0.7N
2.30 *44½*	1.56 *55½*	1.83 *2½*	1.64 *4½*	1.52 *8½*	1.45 *40*	0.51 *6½*	1.68 *33½*	0.24 *4*	0.70 *3*	1.10 *14½*	2.39 *7*	2.94 *3*	3.62 *2*
2.27 *47*	1.26 *53*	1.76 *3½*	1.56 *5*	1.38 *9½*	1.17 *35*	1.51 *4*	1.07 *31*	0.48 *19*	1.0 *2½*	1.2 *5*	1.8 *3½*	3.8 *½*	5.3 *½*
0.42 *20*	0.13 *80*	0.12 *2*	0.13 *4*	0.15 *10*	0.14 *64*	— *0*	0.14 *64*	0.04 *48*	0.13 *4*	0.30 *9½*	0.52 *2*	0.60 *¼*	0.45 *¼*
1.48 *35*	0.80 *65*	0.95 *2*	0.87 *3*	0.84 *8*	0.77 *52*	0.80 *6*	0.75 *46*	0.30 *17*	0.45 *6*	0.68 *13*	1.50 *8½*	2.60 *1*	4.60 *½*
3.60 *77*	3.74 *23*	2.5 *1*	3.86 *2*	3.41 *4*	3.58 *16*	1.95 *6*	4.58 *10*	— *0*	— *0*	— *0*	3.64 *4*	5.14 *4*	6.32 *2*
1.09 *41*	1.08 *59*	1.1 *3*	1.09 *3*	0.99 *8*	1.00 *45*	0.5 *2*	1.07 *43*	— *0*	— *0*	0.3 *2*	0.7 *4*	1.0 *1½*	1.10 *35½*
2.13 *70*	3.45 *30*	3.04 *1*	3.06 *3*	3.04 *6*	3.78 *20*	0.90 *11*	7.86 *9*	0.50 *½*	1.30 *1*	4.00 *2*	3.60 *2*	12.48 *2*	5.60 *1½*
0.88 *83*	1.01 *17*	0.8 *1*	1.00 *1*	0.94 *3*	0.99 *12*	0.30 *7*	1.86 *5*	— *0*	— *0*	1.35 *1*	2.27 *2½*	1.20 *1*	1.25 *½*
1.45 *56*	0.99 *44*	1.20 *1½*	1.15 *2½*	1.04 *7*	0.99 *33*	0.73 *8½*	1.10 *24½*	0.39 *7½*	0.75 *1½*	0.91 *7*	0.78 *6½*	1.85 *1½*	2.75 *½*
3.09 *62*	2.12 *38*	3.45 *3*	3.09 *3*	2.69 *5*	2.29 *27*	1.14 *13*	3.00 *14*	— *0*	1.3 *2*	2.16 *4½*	3.62 *4½*	4.08 *2½*	5.6 *½*
0.72 *66*	0.85 *34*	1.22 *1*	1.00 *2*	0.80 *5*	0.84 *26*	0.50 *16*	1.37 *10*	— *0*	— *0*	1.18 *3*	1.28 *6*	2.25 *½*	7.1 *½*
1.80 *54½*	1.60 *45½*	1.70 *2*	1.72 *3*	1.58 *6½*	1.60 *34*	0.81 *7*	2.34 *27*	0.16 *9*	0.34 *2*	1.21 *5½*	2.23 *4½*	3.61 *1½*	4.09 *4½*

(table 6) could well be due to variations in the amounts of zircon in the original samples.

ECONOMIC OUTLOOK

The thorium and rare-earth deposit at Morro do Ferro offers some promise as a significant source of these elements. Review of the data presented in this report suggests that the near-surface central zone of the deposit will contain, per meter of depth, over a million metric tons of material that averages close to 1 percent thoria and 4 percent total rare-earth oxides. A significant secondary reserve of lower grade material surrounds the higher grade "core" discussed above. The data available indicate that the tonnage of this peripheral zone will exceed half a million tons averaging about ½-percent thoria and, if the TREO:$eThO_2$ ratios of the central zone can be extended outward, about 1½–2½ percent total rare-earth oxides. In actuality, no definite outward limit of the "ore body" has yet been established; mining limits will depend upon the selection of an "economic" cutoff grade.

The depths to which these average grades can be maintained is highly problematical and will not be known until considerably more underground data are available. The vertical variability of radioactivity, as measured by the gamma-ray logging of open drill holes, suggests a decreasing average grade downward because the quantity of higher grade material becomes more spotty or pockety with depth.

In spite of the apparent decrease in grade with depth, the amount of readily available "ore" must be considered in millions of metric tons. The bulk of this material should be highly amenable to large-scale open-pit development because of its near-surface occurrence and its highly decomposed, lateritic condition. The main obstacles to open-pit mining with large mechanized earth-moving equipment would be the hard, resistant ledges formed by the larger unweathered magnetite dikes. The chief problem in the utilization of the Morro do Ferro ore will be in devising a scheme of benefication or extraction that will permit this material to be competitive with other sources of these elements. The meager data thus far available suggest that attempts to beneficiate the ore solely by physical methods will not be particularly successful. Doubtless some method of chemical leaching, perhaps in combination with the prior magnetic removal of most of the magnetite and hematite, may prove more feasible.

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