Geologic Distribution and Resources of Thorium

GEOLOGICAL SURVEY BULLETIN 1204

Prepared partly on behalf of the U.S. Atomic Energy Commission

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By J. C. OLSON *and* W. C. OVERSTREET

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GEOLOGIC DISTRIBUTION AND RESOURCES OF THORIUM

By J. C. OLSON and W. C. OVERSTREET

ABSTRACT

Thorium is a great potential source of energy. Owing to the small quantity of thorium thus far required for reactor development, little exploration has been made for it compared to that made for other metals. Concentrations of thorium are found chiefly in four geologic environments: (1) placer deposits, source of most of the production, which consist of beach, fluviatile, and residual (eluvial) concentrations of heavy thorium-bearing minerals; (2) epigenetic deposits, which include vein or lode deposits and contact-metamorphic or replacement bodies; (3) sedimentary rocks, which comprise ancient placers, thorium-bearing dolomite, and deposits in conglomerates; (4) igneous and metamorphic rocks, which include thorium-rich granite, alkalic rocks, carbonatite, fenite, pegmatite and pegmatitic migmatite, and thorium-rich zones in metamorphic rock.

Known thorium reserves of the United States are estimated at about 100,000 tons ThO_2. Total resources are probably much larger for additional thorium will no doubt be found in undiscovered districts and at unexplored depths in known districts. Known world reserves in high-grade deposits and easily mined placer deposits are about 740,000 tons, but total world resources of thorium, including undiscovered deposits, may well be at least several million tons ThO_2. A comparison of crustal abundance of various metals with known reserves suggests, as a speculative estimate, that world ThO_2 resources in high-grade deposits and easily mined placer deposits may ultimately be on the order of 10 to 20 million tons. These deposits must be considered largely as high-cost resources until economic conditions and increased geologic and exploratory efforts make their discovery possible. Potential low-grade thorium resources are undoubtedly very large.

INTRODUCTION

Thorium is a great potential source of energy because the common, naturally occurring isotope Th^{232} can be transmuted into fissionable U^{233}. Through bombardment by slow neutrons, Th^{232} is converted to Th^{233}, which decays through Pa^{233} into U^{233}. In a breeder reactor this process yields more nuclear fuel than is consumed. Through the utilization of thorium and uranium in breeder reactors, the world's supply of energy is vastly increased over that which would be available only from the fossil fuels.

Reactors have thus far required little thorium; in 1961 only 121 tons of ThO_2 was consumed (Baker and Tucker, 1962, p. 1210), and over 90 percent of this amount was used in thorium-magnesium alloys and gas mantles. The limited demand has discouraged intensive prospecting and development of deposits. Consequently, knowledge of thorium distribution tends to lag behind that of other more widely used mineral commodities.

The small amount of information obtained directly through thorium exploration is augmented somewhat by discoveries made in prospecting for uranium by radiometric surveys, for the thorium series, although somewhat less radioactive than the uranium series, is readily detectable by radiometric methods.

Although qualitative data about the geologic occurrence and behavior of thorium in the earth's crust are rather plentiful, quantitative data on the grade and extent of both high-grade and submarginal resources are meager compared to that for many other metals or fuels. Little mining has been done, and very few high-grade deposits have been explored at depth. Many abnormal concentrations of thorium found by radioactivity-detection methods have not yet been thoroughly evaluated. Much is still to be learned about the abundance and distribution of thorium in rocks that contain about 0.01 to 0.1 percent ThO_2 and are submarginal under current economic and technologic conditions.

The data assembled for this paper, because of their insufficiency and varying degrees of reliability, do not in general justify a sophisticated analytical treatment to yield precise resource figures, but they do permit rather tenuous extrapolations as to the general order of magnitude of thorium resources.

The present report is an outgrowth of investigations made by the Geological Survey on behalf of the Atomic Energy Commission. It incorporates data on thorium deposits from numerous sources in the literature and from the staffs of the Geological Survey and Atomic Energy Commission. Information on thorium in specific areas or rocks was contributed by M. R. Brock, David Gottfried, D. C. Hedlund, E. M. MacKevett, George Phair, D. L. Schmidt, Q. D. Singewald, and G. W. Walker of the Geological Survey. R. D. Nininger and others of the Atomic Energy Commission provided some of the information on known reserves in the United States as well as current reserve estimates of certain countries shown in table 4.

PRODUCTION

Total cumulative world production of thorium has been less than 20,000 tons (U.S. Atomic Energy Commission, 1959). The production of monazite, the principal source material of thorium and rare earths, is illustrated in figure 1 for the period 1893–1947 and in table 1 for 1948–62.

A few tons of monazite was produced in the United States in 1887 and steady production began in 1893 (fig. 1). The increased world production from 1895 to 1921 reflects the demand for thoria and minor amounts of ceria for use in the incandescent gas mantle industry. This use declined after World War I. From 1921 to 1934, little monazite, used largely for its rare earth content, was produced, and thoria, used in making of gas mantles, was a minor byproduct. From 1950 to the present (1964) monazite has again been mined chiefly for its thorium content for uses in atomic energy and other fields. During the late 1950's the United States annually used as much as 11,000 tons of monazite containing 6 percent ThO_2 (Kremers, 1958), but after 1958 consumption declined. Although at the 11,000-ton rate of consumption the United States undoubtedly could supply its own thorium needs for many years, generally higher costs have virtually limited production of monazite to that obtained by heavy-mineral dredging operations in South Carolina and in Florida. The dredging operations in South Carolina were abandoned in 1958.

Before 1909 the United States imported no monazite but processed its own, although after 1904 it imported thorium nitrate (Pratt, 1916, p. 68). Brazil dominated the monazite mining industry from 1895 until 1914 and shipped most of the product to Germany for refining. India supplied most of the world's monazite from 1914 until 1946, when an embargo was placed on the export of monazite and other sources of fissionable materials. Brazil was again a major producer during 1947–50, but restricted the export of thorium after January 1, 1951.

In recent years, sources of supply for thorium and rare earths have become increasingly widespread (table 1). Before 1948, thorium came chiefly from monazite found in the beach sands of India and Brazil, but recently it has been obtained from various minerals in several geologic environments. During 1953–59, a vein deposit at Steenkampskraal, in the Van Rhynsdorp district, South Africa, provided most of the free world's monazite; it yielded 16,230.7 tons during 1953–56 (Pike, 1958). The mine closed in March 1959 but reportedly was reopened in 1962. Byproduct thorium and rare earths are obtained from rutile-zircon deposits in Australia and from placer tin-mining operations in Malaya and Indonesia. In 1959, uranium mills in the Blind River field, Ontario, began supplying byproduct thorium, and it was expected that they would produce from 100 to 200 tons of thorium concentrates per year. Since 1955 the Malagasy Republic has been one of the greatest sources of thorium. It has annually produced from 250 to 300 tons of thorium metal in the form of thorium

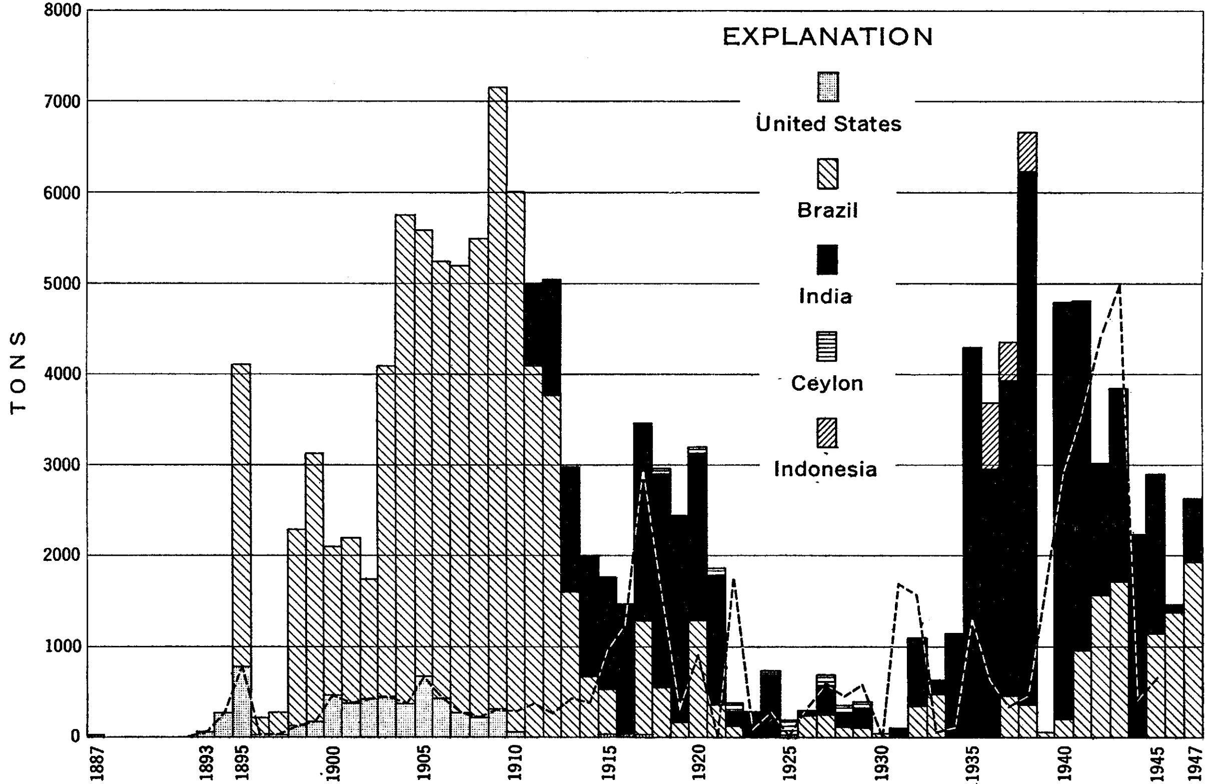

FIGURE 1.—World production of monazite, short tons, 1893–1947. Data from U.S. Bureau of Mines, Minerals Yearbook, various years, in part summarized by Mertie (1953, p. 6). Data are incomplete after 1938. Figures for India for 1940–47, which are based on Krishnan (1951, p. 298), may not be complete. Dashed line is total United States production plus imports.

TABLE 1.—*World production, in short tons, of monazite concentrates, 1948–62*

[From U.S. Bur. Mines, 1963]

Country [1]	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
North America: United States	[2] 40	(3)	767	1,497	2,229	1.232	1,971	1,219	(3)	[2] 2,006	[2] 722	[2] 770	(3)	(3)	(3)
South America:															
Argentina	-----	-----	-----	-----	-----	-----	-----	-----	1	-----	-----	-----	-----	-----	-----
Brazil	[4] 1,968	[4] 2,387	(5)	(5)	(5)	(5)	2,976	(5)	(5)	(5)	1,162	1,222	1,153	[6] 930	[6] 930
Asia:															
Ceylon	-----	-----	-----	-----	16	56	51	67	58	150	124	94	370	239	-----
India	(5)	(5)	(5)	530	(5)	(5)	(5)	(5)	(5)	(5)	4,122	(5)	(5)	(5)	(5)
Indonesia	-----	-----	-----	-----	-----	314	11	122	(5)	(5)	(5)	(5)	(5)	111	153
Korea [7]	-----	-----	-----	-----	903	845	1,108	560	203	392	355	65	11	854	(5)
Malaya (exports)	-----	-----	-----	84	63	208	391	279	707	549	479	264	47	780	702
Thailand	-----	-----	-----	-----	-----	-----	-----	-----	18	64	1	(5)	(5)	(5)	(5)
Africa:															
Congo, Republic of the	-----	-----	-----	41	15	12	4	5	1	-----	-----	-----	-----	-----	-----
Malagasy Republic (Madagascar)	-----	-----	-----	-----	-----	-----	-----	72	168	331	-----	-----	471	503	702
Mozambique	-----	-----	-----	-----	-----	-----	-----	-----	-----	(8)	(8)	-----	1	(8)	(5)
Nigeria	-----	-----	-----	(5)	6	-----	-----	-----	86	104	64	15	13	8	10
South Africa, Republic of	-----	-----	-----	-----	[6] 300	[6] 5,000	[6] 9,000	[6] 9,000	[6] 9,000	9,314	8,112	2,402	-----	-----	5,326
United Arab Republic (Egypt)	7	3	80	1	7	7	9	1	7	(5)	(5)	[6] 165	(5)	(5)	(5)
Oceania: Australia [9]	942	1,510	1,337	1,864	129	283	199	216	268	496	508	401	405	1,839	1,091
Total (items listed only) [1]	2,957	3,900	2,184	4,017	3,668	7,957	15,720	11,541	10,517	13,406	15,649	5,398	2,471	5,264	8,914

[1] Monazite is also produced in U.S.S.R., but data not available.
[2] Shipments.
[3] Figure withheld to avoid disclosing individual company confidential data.
[4] Exports.
[5] Data not available.
[6] Estimate.
[7] Reported as concentrates containing 45–55 percent of R_2O_3; also reported as 30 percent Ce, which may be high.
[8] Less than 0.5 ton.
[9] The data listed represent the total for the three classes: high-grade, low-grade concentrate, and concentrate.

nitrate, as a byproduct of uranium extracted from thorianite (Mabile, 1958). Carbonatites in several areas in the United States, Africa, Scandinavia and Brazil have become potential sources of rare earth-, niobium-, and thorium-bearing minerals. Vein deposits of thorite are also potential sources of thorium.

GEOLOGIC FACTORS IN THE CONCENTRATION OF THORIUM INTO WORKABLE DEPOSITS

The thorium content of the earth's continental crust has recently been estimated to be about 11.4 ±2 ppm (parts per million) (Adams and others, 1959). Other estimates, made by nine investigators and compiled by Fleischer (1953), range from 0.00073 to 0.002 percent. The greatest part of the thorium is widely disseminated in small quantities which differ in amount according to rock type. The geochemistry of thorium is quite different from that of uranium. Unlike many uranium deposits, large thorium deposits have not been formed by deposition from low-temperature fluids in a near-surface environment. The principal concentrations of thorium occur as detrital minerals in placer deposits, and in veins, carbonatites, and other rocks formed under generally high pressure-temperature conditions commonly associated with residual magmatic fluids.

In its geochemical cycle, thorium becomes concentrated during several episodes—chiefly in magmatic differentiation and associated hydrothermal activity, weathering, transportation and deposition of thorium-bearing minerals, and metamorphism. Among the most important factors in the formation of workable deposits are (1) the composition of igneous rock with which thorium is associated, which may be related to magmatic differentiation, (2) the type and grade of metamorphism of thorium-bearing rocks, (3) the availability of potential source rocks for concentration or reconcentration of thorium-bearing detrital minerals in placer deposits, (4) type of weathering of source rocks of detrital thorium minerals, and (5) favorable geomorphic features for transportation and deposition of thorium-bearing minerals in placer deposits.

In the course of magmatic crystallization, some thorium is a constituent of accessory minerals such as apatite, sphene, allanite, thorite, monazite, and zircon, and some is deposited in intergranular films in the igneous rocks. Because of its large ionic radius and high valence, thorium tends to become concentrated in the residual solutions as crystallization continues. Thus it is most abundant in the younger members of rock series, such as granitic and alkalic rocks, particularly in rocks formed from residual magmatic fluids, such as some veins, carbonatites, and pegmatites.

The composition of the igneous rock with which thorium may be associated is a factor in evaluating thorium potential. As shown by examples on table 2, the thorium content of igneous rocks is likely to be higher in granite than in granodiorite or quartz monzonite. Cassiterite-bearing granite typically contains accessory thorium-bearing minerals such as allanite, monazite, or thorite. Bodies of cassiterite-bearing granite may well contain more thorium than is indicated by their content of thorium-bearing minerals, although little cassiterite-bearing granite has been analyzed for total thorium content. The thorium content is commonly high in alkalic granites and syenites, and it is notable in small alkalic rock complexes with which carbonatite is associated. Thus, in evaluation of the potential of an area for thorium in low-grade igneous rock sources, or for richer concentrations in veins or carbonatite, areas of alkalic rocks, granite, or syenite are more favorable than those of most other types of igneous rocks.

In metamorphic and magmatic environments—under the highest pressure-temperature conditions—both the abundance and the thorium content of monazite in metamorphic rocks increase as the grade of metamorphism increases (Overstreet, 1960). Accessory monazite is extremely rare in the greenschist facies, rare to sparse in the epidote-amphibolite facies, sparse to common in the amphibolite facies, and common to abundant in the granulite facies.

In rocks in which little or no monazite is present and that have undergone only the lower grades of metamorphism, the thorium is in allanite and in other common minerals not as readily susceptible as is monazite to mechanical concentration in placer deposits. Apparently monazite is less common and allanite more common in granite, granodiorite, and syenite formed under low- and intermediate-grade metamorphic conditions than in those formed under high-grade metamorphic conditions. Accordingly, in evaluation of a terrane for monazite concentrations in metamorphic rocks and also for placers of potential economic value, high-grade metamorphic or related igneous rocks are considered to be the most favorable source rocks. Such rocks are also likely to have more thorium-bearing veins and pegmatites, although thorium-bearing veins are also found in some other areas of igneous rocks of alkalic affinities. Because high-grade metamorphic and igneous rocks are generally more abundant in Precambrian terrane than in areas of younger rocks, the thorium potential of large areas or regions is very roughly proportionate to the area of Precambrian rock exposed. Relation of thorium reserves of various parts of the world to areas of Precambrian and other high-grade metamorphic and igneous rocks is shown in table 4.

The thorium disseminated in rocks of the crust, on weathering of the rock, is virtually insoluble and does not migrate appreciably in ordinary surface or ground water. The rivers, lakes, and oceans contain very little thorium. Most thorium minerals, on weathering and disintegration of the enclosing rock, remain as detrital grains owing to their insolubility and generally high specific gravity. The weathered mantle thus becomes enriched in residual heavy minerals which gradually move downslope and downstream. Placers are formed in places where the stream gradient permits transportation of lighter and smaller particles while the heavier and larger particles remain behind. Most of the monazite and other heavy minerals that reach the sea are deposited near shore at the mouths of rivers. Some thorium that is not in the heavy detrital mineral component of the bedrocks is apparently adsorbed during weathering in clay minerals and after deposition is disseminated in clayey sediments. In marine sedimentary rocks, therefore, thorium is found either in detrital minerals deposited in near-shore sands, in which some economic placer concentrations occur, or disseminated in claystone or shale in which no economic concentrations are known.

The degree and depth of weathering are important in evaluation of thorium resources. Weathering may result in residual concentration of thorium in the soil overlying a deposit and in the release of resistant grains such as monazite. Tropical weathering, during which the enclosing minerals are decomposed by chemical processes, is more effective in segregating heavy minerals than is the dominantly mechanical weathering of arid climates. The physical decomposition of a granular rock, as occurs in arid regions, releases large amounts of feldspar and quartz to the sands and thereby dilutes the heavy-mineral concentration.

Allanite weathers easily; rare earths are commonly lost and a pulverulent material of low specific gravity is formed which disintegrates readily and is not amenable to gravity concentration. Therefore, in humid regions allanite does not form placers. In arid regions where rocks undergo mechanical disintegration, unweathered allanite may be concentrated locally by transport and deposition in intermittent streams, although such allanite placers are not yet known in the United States.

Another factor that may enhance the thorium potential of a region is the possibility that detrital monazite in older sedimentary rocks may be eroded and reconcentrated by modern streams or by the sea.

In summary, concentrations of thorium are chiefly of the following geologic types:

- Igneous and metamorphic rocks:
  - Dikes or layers of alkalic rock
  - Carbonatite
  - Fenite
  - Thorium-rich granite
  - Pegmatite and pegmatitic migmatite
  - Thorium-rich zones in metamorphic rock
- Epigenetic deposits:
  - Vein or lode deposits
  - Contact-metamorphic and replacement bodies
- Placer and residual concentrations:
  - Residual concentrations in place
  - Beach placers
  - Stream or valley placers
- Sedimentary rocks:
  - Ancient placer concentrations
  - Thorium-bearing dolomite
  - Thorium-uranium deposits of Blind River type in conglomerate

GEOLOGIC DISTRIBUTION OF THORIUM RESOURCES

IGNEOUS ROCKS

The approximate thorium content of various rocks is given in table 2. The highest concentrations of thorium in a given series of igneous rocks generally are found in the youngest members of the series. Voluminous data indicate that the closer the natural rocks approach petrogeny's residua system as defined by Bowen (1937), which includes both quartz-bearing and feldspathoidal types, the higher their Th content (George Phair and David Gottfried, written commun., 1962). For most quartz-bearing silicate rocks, diminishing CaO content is a useful index to potential high-thorium igneous rocks. For example, the quartz bostonite dikes of the Central City district, Colorado, which contain as much as 400 ppm Th, contain only 0.2 to 0 percent CaO (George Phair, written communication, 1962). Among alkalic rock types, however, many calcic igneous rocks are known to contain appreciable amounts of thorium.

Alkalic igneous rocks as a group are rich in thorium but differ considerably in thorium content. Many contain thorium in amounts of 0.02 percent or more, although the extent and content of such rocks are inadequately known. In some alkalic complexes the radioactivity is greatest in carbonatite, if present. In others it is greatest in some of the associated silicate rocks; for example in some pyrochlore-bearing carbonatite areas in Ontario, the most radioactive rocks are silicate rocks containing rare earth and thorium minerals.

TABLE 2.—*Thorium content, in parts per million, of igneous and sedimentary rocks, listed by rock type*

Rock type	Locality	Samples	Content (ppm) Range	Content (ppm) Average	Reference
Igneous rocks					
Silicic rocks:					
Riebeckite granite	Kaffo, Nigeria		200–300		Mackay and Beer (1952).
Granite (Tokovskii Complex).	Middle Dnepr region, U.S.S.R.	101		97	Filippov and Komlev (1959).
Granite, granophyre, aplite, and pegmatite. (Variscan age).	Northern Kirghizia, U.S.S.R.	126		70	Turovskii (1957).
Granite (Conway Granite).	New Hampshire	580	30–110	56	Adams and others (1962).
Granodiorite	Mount Whitney, Calif.	1		52	Rogers and Ragland (1961).
Granite	Westerly, R.I.	1	45–61	52	Stevens and others (1960).
Alaskite	Kzyl-Ompul massif, Northern Tien-Shan, U.S.S.R.	4	42.7–57.8	50.9	Leonova and others (1961).
Biotite granite (White Mountain Plutonic-Volcanic Series).	New Hampshire	12	30–77	46	Butler (1961).
Granite	Pikes Peak, Colo.	2	37–39	38	Whitfield and others (1959).
Granite (Yustyd Complex).	Tuva, U.S.S.R.	6		36	Abramovich (1959).
Aplite (New Hampshire Plutonic Series).	New Hampshire	5	4.3–57	35	Lyons (1961).
Alkalic granite and rhyolite.	Big Bend, Tex.	7	24–45	34	Gottfried and others (1962).
Granite	Alps			33	Jeffreys (1952)
Granite (Precambrian)	Northern Kirghizia, U.S.S.R.	16		33	Turovskii (1957).
Granite (Kirovograd-Zhitomir Complex).	Middle Dnepr region, U.S.S.R.	100		33	Filippov and Komlev (1959).
Granite	Rhode Island	4	16–64	32	Brown and others (1963).
Do	Kyzyltau massif, Central Kazakhstan, U.S.S.R.	59		31	Baranov and DuLieh-t'ien (1961).
Granite (Lebanon Granite).	Lebanon, N.H.	2	28–33	30.5	Rogers and Ragland (1961).
Granite	Finland			28	Jeffreys (1952).
Do	Southwestern Maine	22	11–78	28	Brown and others (1963).
Hastingsite granite	New Hampshire	2	23–29	26	Rogers and Ragland (1961).
Amphibole granite	New Hampshire	5	14–40.5	25.3	Butler (1961).
Granite (Chingekat Complex).	Tuva, U.S.S.R.	12		24	Abramovich (1959).
Quartz monzonite (Mascoma Group).	New Hampshire	4	16–32		Rogers and Ragland (1961).
Granite	Massachusetts	9	9–38	19	Brown and others (1963).
Granite (Caledonian age)	Northern Kirghizia, U.S.S.R.	51		19	Turovskii (1957).
Biotite-quartz monzonite of Merrymeeting stock.	New Hampshire	1		18.7	Butler (1961).
Granite (Cathedral Peak Granite).	Mount Whitney, Calif.	2	16–21	18.5	Rogers and Ragland (1961).
Monzonite (White Mountain Plutonic-Volcanic Series).	New Hampshire	2	14–20	17	Do.
Leucogranite (Roblar Leucogranite).	California	1		17	Do.

TABLE 2.—*Thorium content, in parts per million, of igneous and sedimentary rocks, listed by rock type*—Continued

Rock type	Locality	Samples	Content (ppm) Range	Content (ppm) Average	Reference
Igneous rocks—Continued					
Silicic rocks—Con.					
Granite, quartz monzonite, and granodiorite (Oliverian Plutonic Series).	New Hampshire	20	6.2–38	16.3	Lyons (1961).
Red granite	North America	13		16.2	Whitfield and others (1959).
Granite	Rocky Mountain region, United States.	11		15.7	Do.
Granite, quartz monzonite, and granodiorite (New Hampshire Plutonic Series).	New Hampshire	48	9.1–28.5	15.7	Lyons (1961).
Microcline granite (Syutkhol Complex).	Tuva, U.S.S.R.	21		15	Abramovich (1959).
Granite (Precambrian)	North America	24		14	Whitfield and others (1959).
Granodiorite	California and Idaho	38	3–24		Rogers and Ragland (1961).
Granite and rhyolite	United States and Canada.	12	0–25	13.4	Evans and Goodman (1941).
Tonalite and granite (Tannu-ola Complex).	Tuva, U.S.S.R.	12		13	Abramovich (1959).
Quartz monzonite and granodiorite (Highlandcroft Plutonic Series).	New Hampshire	4	10.6–14.8	12.4	Lyons (1961).
Granodiorite	California	5	10–14		Rogers and Ragland (1961).
Granite	Canadian Shield, Canada.	7		11	Whitfield and others (1959).
Granophyre	Fairfax County, Va.	4	8.2–13.1	10	Larsen and Gottfried (1960).
Granite (Boundary Peak and Pellisier Granites).	California	2	8.2–11	9.6	Rogers and Ragland (1961).
Granite (post-Cambrian)	North America	25		8.6	Whitfield and others (1959).
Granite	West coast of United States.	16		8.5	Do.
Do	North America, Greenland, Iceland, Scotland, Ireland, and Japan.			8.1	Jeffreys (1952).
Do	12 areas, North America.	12	0.9–19.3	7.9	Keevil (1938).
Granite (Khovaksin Complex).	Tuva, U.S.S.R.	4		5	Abramovich (1959).
Pegmatite (Oliverian and New Hampshire Plutonic Series).	New Hampshire	5	2.8–5	4	Lyons (1961).
Alkalic and syenitic rocks:					
Lujavrite	Ilimaussaq, Greenland.		300–800		Bondam and Sörensen (1958).
Quartz bostonite	Central City, Colo.	14	100–408	240	George Phair (written commun., 1962).
Granosyenite and quartz syenite.	Northern Kirghizia, U.S.S.R.	8		185	Turovskiĭ (1957).
Hornblende-albite syenite	Wet Mountains, Colo.	3	150–200		Christman and others (1959); George Phair (written commun., 1962).
Syenite	Northern Kirghizia, U.S.S.R.	97		74	Turovskiĭ (1957).
Do	Kzyl-Ompul massif, Northern Tien-Shan, U.S.S.R.	6	44.5–92	62.9	Leonova and others (1961).
Quartz syenite	do	6	36.6–60.2	50.3	Do.
Nepheline syenite	Augusta County, Va.	11	30–87	48	Gottfried and others (1962).
Phonolite and tephrite	Kaiserstuhl, West Germany.	2	42.5–43.3	43	Seith (1927).
Cancrinite syenite	Kola Peninsula, U.S.S.R.	1		33	Polyakov and Volynets (1961).

TABLE 2.—*Thorium content, in parts per million, of igneous and sedimentary rocks, listed by rock type*—Continued

Rock type	Locality	Samples	Content (ppm) Range	Content (ppm) Average	Reference
Igneous rocks—Continued					
Alkalic and syenitic rocks—Con.					
Amphibole-biotite syenite	Belknap Mountains, N.H.	2	25–33.5	29.3	Butler (1961).
Quartz syenite	Pilot Range, N.H.	1		27	Do.
Trachyte, trachyandesite, and analcite syenite.	Big Bend Natl. Park, Tex.	7	9.5–40	15.5	Gottfried and others (1962).
Pyroxene syenite (White Mountain Plutonic-Volcanic Series).	New Hampshire	2	9.5–10.2	9.9	Butler (1961).
Quartz syenite (White Mountain Plutonic-Volcanic Series).	do	2	3.4–10	6.7	Rogers and Ragland (1961).
Syenite, basalt, syenodiorite, syenogabbro, nepheline basalt, and related rocks.	Big Bend Natl. Park, Tex.	13	2.6–11	5.1	Gottfried and others (1962).
Intermediate rocks:					
Diorite, quartz diorite, and granodiorite.	Northern Kirghizia, U.S.S.R.	13		30	Turovskiĭ (1957).
Tonalite	Mount Whitney, Calif.	1		24	Rogers and Ragland (1961).
Quartz diorite and tonalite	New Hampshire	8	2.9–14.8	8.3	Lyons (1961).
Diorite (Tannu-ola Complex).	Tuva, U.S.S.R.	8		7	Abramovich (1959).
Quartz diorite (Mascoma quartz diorite).	New Hampshire	1		6.2	Rogers and Ragland (1961).
Tonalite	California and Idaho	17	1.4–18	6.2	Larsen and Gottfried (1960).
Granodiorite and plagiogranite.	Middle Dnepr region, U.S.S.R.	14		5	Filippov and Komlev (1959).
Granodiorite, tholeiite, quartz dolerite, trachyte, and dacite.	United States, Canada, and England.	6	.45–10	4.4	Evans and Goodman (1941).
Tonalite (Bonsall Tonalite).	California	3	3.1–4.2		Rogers and Ragland (1961).
Andesite, dacite, rhyolite, and basalt.	Strawberry Mountain, Oreg.	8	1.3–6.4	3.6	Gottfried and others (1963).
Dacite, andesite, basalt, gabbro, and rhyodacite.	Mount Garibaldi, British Columbia, Canada.	13	1–4	2	Do.
Mafic rocks:					
Melteigite, ijolite, and ijolite-urtite.	Kola Peninsula, U.S.S.R.	4	9–44	23.3	Polyakov and Volynets (1961).
Teschenite	Augusta County, Va.	9	7.1–39	19.6	Gottfried and others (1962).
Pyroxenite and jacupirangite.	Kola Peninsula, U.S.S.R.	11	1.3–28	14.7	Polyakov and Volynets (1961).
Picrite	Augusta County, Va.	4	7.8–14.1	11	Gottfried and others (1962).
Basalt	North America, Greenland, Iceland, Scotland, and Ireland.			9.8	Jeffreys (1952).
Do	England, Germany, France, and Hungary.			8.8	Do.
Alkalic basalt (Honolulu Volcanic Series).	Oahu, Hawaiian Islands.	7	2.5–10.3	5.4	Larsen and Gottfried (1960).
Basalt (plateau basalt)	India and Oregon			5.2	Jeffreys (1952).
Basalt	Oceanic islands			4.6	Do.
Basalt, diabase, and traprock	United States, Canada, and Ireland.	17	0–15	4	Evans and Goodman (1941).
Gabbrodiorite (Torgalyk Complex).	Tuva, U.S.S.R.	4		4	Abramovich (1959).
Dunite	World			3.3	Jeffreys (1952).
Gabbro (Tannu-ola Complex).	Tuva, U.S.S.R.	3		3	Abramovich (1959).
Basalt	11 areas, North America and U.S.S.R.	11	1.6–4.4	2.8	Keevil (1938).
Diabase	Fairfax, Va.	11	.8–3.1	2.1	Larsen and Gottfried (1960).
Gabbro and gabbrodiorite (Caledonian age).	Northern Kirghizia, U.S.S.R.	11		2.1	Turovskiĭ (1957).

TABLE 2.—*Thorium content, in parts per million, of igneous and sedimentary rocks, listed by rock type*—Continued

Rock type	Locality	Samples	Content (ppm)		Reference
			Range	Average	
Igneous rocks—Continued					
Mafic rocks—Con.					
Basalt and andesite	Mariana Islands	26	.4–2.4	1.1	Gottfried and others (1963).
Monzodiorite and gabbro (White Mountain Plutonic-Volcanic Series).	New Hampshire	3	.4–2.3	------	Rogers and Ragland (1961).
Tholeiitic olivine basalt	Hawaii	23	.5–1.4	------	Larsen and Gottfried (1960).
Gabbro	Belknap Mountains, N.H.	1	------------	.9	Butler (1961).
Do	California and Idaho	9	.2–1.2	------	Larsen and Gottfried (1960).
Olivinite	Kola Peninsula, U.S.S.R.	2	.5–.8	.7	Polyakov and Volynets (1961).
Sedimentary and residual materials					
Bauxite	Central and South America.	10	34.8–132	67	Adams and Weaver (1958).
Do	United States	7	34.6–96	58	Do.
Do	Southern Europe	5	43.8–59.2	51.5	Do.
Do	East Indies and India	2	23.2–58.7	41	Do.
Do	Gold Coast	1	------------	21.2	Do.
Do	Oregon	1	------------	19.3	Do.
Do	Palau Island	1	------------	5	Do.
Clay, shale, and bentonite:					
Bentonite	North America	69	7.2–42	24	Do.
Gray and green shale	do	52	0–47	13	Do.
Black shale	do	19	1.6–28	12.6	Do.
Red and yellow shale and residual clay.	World	11	7–17	12.3	Do.
Clay or shale	Russian Platform, U.S.S.R.	4,795	7.6–14	11	Baranov and others (1956).
Shale (Chattanooga Shale).	Southeastern United States.	46	8.1–15	10.8	Andrew Brown (written commun., 1962).
Shale (Mancos Shale)	Rocky Mountain region, United States.	135	------------	10.2	Pliler and Adams (1959).
Shale	Europe and Japan	------	------------	10	Minami (1935).
Miscellaneous sedimentary rocks:					
Uranium ores	Blind River, Ontario, Canada.	------	300–1,000	600	Griffith (1963).
Black-sand deposits (Cretaceous age).	Rocky Mountain region, United States.	82	------------	300	Dow and Batty (1961).
Thorium-bearing dolomite.	McLean Bay, Northwest Territories, Canada.	------	------------	250	Lang (1952).
Monazite-bearing quartzite (Goodrich Quartzite).	Northern Michigan	------	110–370	------	Vickers (1956b).
Sandstone	North America	5	1–14.4	5.7	Adams and Weaver (1958).
Carbonate rock	Russian Platform, U.S.S.R.	13	1–7.1	2.4	Baranov and others (1956).
Chemical precipitates	United States	7	.03–3.9	1	Adams and Weaver (1958).
Sandstone (orthoquartzite).	North America (most samples from Galveston, Tex.)	16	.8–4	1.7	Murray and Adams (1958).
Carbonate rock	North America	54	0–6.5	1.7	Adams and Weaver (1958).
Limestone	United States and Canada.	4	.16–3	1	Evans and Goodman (1941).
Chert	------------------------	2	.1–1.6	------	Adams and others (1959).
Halite	------------------------	3	.4–.5	------	Do.
Phosphate rock	------------------------	1	------------	3.9	Do.

The number of carbonatite areas in the world no doubt exceeds 100. At least 60 in Africa are well documented in the literature, and others may have been discovered but not yet publicized. Carbonatite districts in other parts of the world include at least 6 in U.S.S.R., 5 in the United States, 4 in Europe, 8 in Brazil, and 12 in Canada. More than 100 alkalic rocks complexes, with or without carbonatite, have been listed by Agard (1956).

Vigorous exploration for carbonatite since 1950 has resulted in the discovery of large deposits of pyrochlore, monazite, and other minerals containing rare earths, thorium, and other uncommon constituents. Economic interest in carbonatite has centered chiefly on niobium, which occurs in pyrochlore and is generally more abundant than thorium. Many carbonatites contain thorium in abnormal quantities, but little information is available on the percentage. Some bodies appear to contain very little, but many probably contain 50–250 ppm thorium, and local concentrations in some may be as much as 0.3 percent. Samples of three carbonatite dikes, each about 10 feet thick, in the Powderhorn district, Colorado, contain 0.06 to 0.2 percent ThO_2. The thorium content of carbonatite is, at the present, not sufficient for commercial production except as a possible byproduct of mining for niobium, apatite, or other products.

Monazite in carbonatite typically has a very low thorium content, commonly less than 1 percent. Of the carbonatite bodies containing low-thorium monazite, one of the largest is the Kangkangunde deposit in Nyasaland; others containing abundant monazite are at Nkumbwa in Northern Rhodesia, Chilwa and Tundulu in Nyasaland, and Mrima in Kenya. Most of the thorium in these rocks may be in the pyrochlore, in which a thoria content of 2 to 3 percent is common; some is in other minerals. According to Pike (1958), the Loolekop carbonatite at Palabora, Transvaal, contains disseminated uranothorianite having a varied thorium-uranium ratio that averages about 3:1, but pyrochlore is said to be absent. He also reported that the carbonatite was explored to a depth of 600 feet, and it was penetrated to a depth of 1,893 feet in one drill hole. He estimated the reserves to be 300 million tons per 1,000 feet of depth and to contain 0.5 lbs. per ton equivalent thorium oxide (Pike, 1958).

Radioactive apatite-rich rocks and nepheline syenite at Araxa and Salitre in Brazil are rich in niobium (pyrochlore) and contain abundant thorium and rare earths. The Araxa carbonatite is reported (Guimaraes, 1957) to be one of the world's largest niobium deposits, and thorium could be recovered as a byproduct.

In Norway, thorium occurs in carbonatite in the Fen area and in thorium-bearing impregnations in syenite in the Langesunds area.

The indicated and inferred reserves in these rocks with not less than 0.01 percent ThO_2 are said to be extremely large (Parker, 1962, p. 56).

Five areas containing carbonatite are known in the United States: Mountain Pass, Calif., Powderhorn and the Wet Mountains, Colo., Magnet Cove, Ark., and Bearpaw Mountains, Mont. In addition, the carbonate rocks in the Mineral Hill district, Idaho, have some features resembling carbonatite. Data on thorium content of the carbonatites of all these areas are inadequate but suggest that considerable parts of the bodies may contain about 50 to 300 ppm thorium; hence, the known carbonatites may contain on the order of several hundred tons of thorium per foot of depth.

Pegmatites are possible sources of small quantities of thorium. Generally they are low in grade and small in size, however, and the thorium minerals disseminated in certain zones in pegmatites are not sufficiently concentrated to mine except as a byproduct of mining for other pegmatite minerals such as feldspar, mica, and quartz. A few exceptional pegmatite areas, particularly alkaline granite or syenite pegmatite, contain high concentrations of thorium that might be minable as the principal product, but very few such areas would contribute appreciably to thorium reserves. Some areas of pegmatized gneisses probably are large and contain enough thorium to be included among the very low grade resources.

Thorium in pegmatite occurs chiefly in such minerals as monazite, allanite, thorite, columbates and titanates, xenotime, gadolinite, and thorianite. Localities from which small quantities of some of these minerals have been produced, in part as a byproduct, include nepheline syenite pegmatite areas in Norway and the Kola Peninsula, U.S.S.R., and granite pegmatite areas in Norway, Sweden, Japan, Korea, and Colorado. Pegmatites in the St. Peters Dome area, Colorado, and at Wausau, Wis., contain such minerals as thorite, thorogummite, zircon, and bastnaesite. Considerable prospecting of these deposits for thorium, niobium, and rare-earth minerals has been done in recent years. Data on some pegmatite districts in the United States that contain thorium minerals have been compiled by Olson and Adams (1962).

The total amount of thorium in all igneous and metamorphic rocks in the United States is of course enormous and could be approximated by applying a factor of 12 ppm to the tonnage of igneous and metamorphic rocks. On the basis of about 80 samples from typical calc-alkalic suites of rocks underlying about 50,000 square miles, the Mesozoic batholiths of the Western United States are estimated to contain roughly 6×10^9 tons of thorium to a depth of 1 mile (David Gottfried, written commun., 1962). This estimate is based on a weighted average of 10 ppm thorium and 2.5 ppm uranium, which is well below the grade of materials included as potential resources in this report. Large masses of granite are known that have a thorium content ranging from about 30 to 50 ppm; resources of this type of material appear virtually inexhaustible.

Igneous rock bodies known to contain more than 100 ppm thorium (fig. 2) are all small, most being less than a square mile in extent. Five narrow quartz bostonite dikes in the Central City district, Colorado, for example, are estimated to contain about 16,000 tons of ThO_2 from surface to a depth of 1,000 feet, if size and grade remain constant (George Phair, written communication, 1962).

Among the larger granitic masses in the United States, the Conway Granite of New Hampshire and the Elberton Granite and Lithonia Gneiss of Georgia (Grunenfelder and Silver, 1958) contain significant amounts of thorium and have been studied in some detail. Adams and others (1962) have shown that the Conway Granite contains 56 ± 6 ppm thorium, totaling over 3 million tons of thorium metal per 100-foot depth in the main Conway batholith alone. The Conway Granite contains, in addition, about 13 ppm uranium (Butler, 1961.)

Recovery of thorium from granitic rock has been studied by the Chemical Technology Division of Oak Ridge National Laboratory. Brown and others (1963) have tabulated the results of studies of 17 granite samples from various areas in the United States ranging in thorium content from 8 to 94 ppm, and in uranium content from 2 to 19 ppm. The total estimated recovery cost for thorium plus uranium in these samples ranged from $30 to $590 per pound. Most of the recent studies have been of the Conway Granite of New Hampshire, chiefly because of its thorium content and process behavior. In 13 Conway Granite samples studied, thorium content ranged from 36 to 106 ppm and averaged 58 ppm. From 52 to 85 percent (or an average of 72 percent) of the thorium was dissolved by the sulfuric acid leach. Estimated recovery costs ranged from $25 to $89 per pound of thorium plus uranium recovered and averaged $57.

The Elberton Granite, which underlies an area of more than 300 square miles in the vicinity of Elberton, Ga., is rich in thorium and contains about 0.3 percent allanite (Silver and Grunenfelder, 1957). The following information on the Elberton Granite, which was supplied by Leon T. Silver (written commun. 1963), is based on results of research by the Division of Geological Sciences, California Institute of Technology. Samples from 15 quarries and analytical data based on a combination of chemical uranium and radiometric total activity comparison show that the thorium content of the Elberton Granite averages 45±15 ppm. The same work shows that the thorium content of the nearby Lithonia gneiss has an average value of 40±15 ppm in an area of about 5 square miles. Experiments show that it is possible, depending on the conditions, to leach as much as 95 percent of the thorium in these two rocks. Experiments to leach the radioactive elements preferentially in relation to the rest of the rock, however, show the possibility of extracting more than 40 percent of the thorium in a total weight of leached material representing less than 1 percent of the weight of the granite. (See also Brown and Silver, 1956.)

Among the potentially minable concentrations of thorium in igneous rocks in other parts of the world are the thorium- and uranium-rich zones in pegmatitic granite and syenite dikes at Bancroft, Ontario (Robinson and Hewitt, 1958); the thorite-bearing bodies of granite in Nigeria, including the Rayfield-Gona columbite-bearing granite from which a thoritelike mineral containing 20 to 30 percent thorium might be recoverable as a byproduct of columbite mining (Davidson, 1956a); and the laterized granite of Sierra Leone, which might yield 20 lbs of monazite per ton (Davidson, 1956a; Bowie and others, 1955). As much as 0.20 percent ThO_2 has been found in exceptional granitic phases in Rhodesia and elsewhere in Africa (Davidson, 1951).

Several Nigerian riebeckite granites are highly radioactive. Sampling of the granite of Kaffo Valley, for example, indicates that one area of 195 acres may be conservatively estimated to contain about 140 tons ThO_2 per foot of depth, and that it also contains 0.33 percent Nb_2O_5. Nearly all the thorium is in the mechanically separable mineral pyrochlore, which contains 41.1 percent $(Nb, Ta)_2O_5$, 3.1 percent U_3O_8, and 3.3 percent ThO_2 (Mackay and Beer, 1952). A little monazite and thorite is also present. To a depth of 1,000 feet, this rock probably contains about 140,000 tons ThO_2, 70,000 tons uranium, and 1,800,000 tons Nb_2O_5.

Thorium is also associated with niobium and rare earths in banded nepheline syenite in the Kola Peninsula, U.S.S.R. There are said to be large reserves of the mineral loparite, which constitutes 2 to 20 percent of six different layers of rock, the thicknesses of which range from 0.5 to 20 meters (Davidson, 1956a). The loparite contains 9 to 12 percent Nb_2O_5, 40 percent TiO_2, 33 percent rare earths, and 0.6 to 0.9 percent thorium.

Similar thorium-rich igneous rocks have been reported in Greenland (Bondam and Sörenson, 1958). In the Ilimaussaq area, large layer-like bodies of lujavrite contain 300 to 800 ppm thorium. At Kvanefjeld in the same area, analcime-rich nepheline syenite bodies contain considerable thorium reserves that have an average grade of 1,920 ppm.

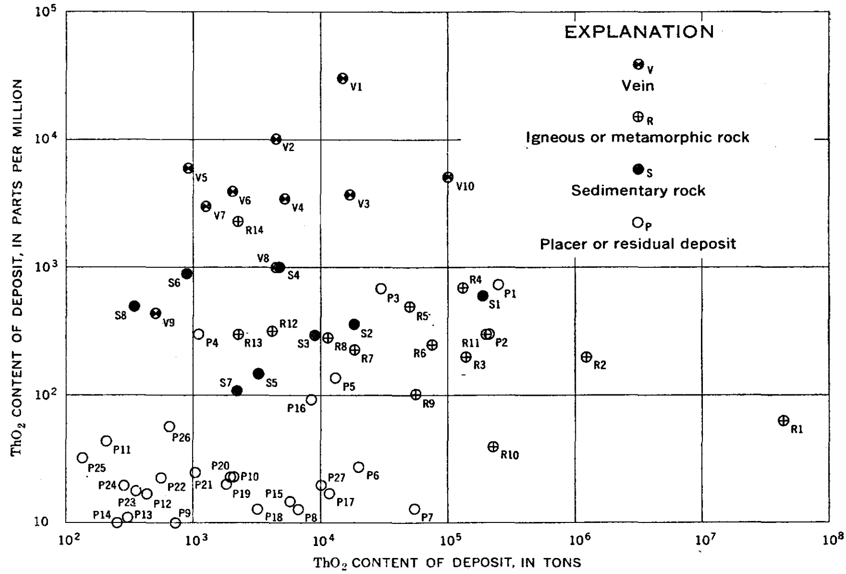

FIGURE 2.—Size and grade of various types of thorium deposits.

R1______ Conway Granite,[1] New Hampshire (based on Adams and others, 1962).
R2______ Hornblende-albite syenite,[1] Wet Mountains, Colo. (M. R. Brock, written commun., 1962).
R3______ Kaffo Granite,[1] Nigeria, 195 acres (Mackay and Beer, 1952).
R4______ Carbonatite, Araxa, Brazil, to 45-m depth (Guimaraes, 1957).
R5______ Carbonatite,[1] Mrima, Kenya (Coetzee and Edwards, 1959).
R6______ Carbonatite,[1] Palabora, Transvaal, calculated from Pike (1958).
R7______ 5 quartz bostonite dikes,[2] Central City, Colo. (George Phair, written commun., 1962).
R8______ Largest of 5 quartz bostonite dikes[1] (George Phair, written commun., 1962).
R9______ Part of Silver Plume Granite,[1] Colorado (George Phair, written commun., 1962).
R10_____ Part of Boulder Creek batholith,[1] Colorado (George Phair, written commun., 1962).
R11_____ Shonkinite,[1] Mountain Pass, Calif., grade assumed from radiometric determinations.
R12_____ Monazite-rich zone[1] in gneiss, Worcester, Mass. (Johnson, 1951).
R13_____ Monazite-rich zone in gneiss, Southbridge, Mass., to 700-ft depth (Johnson, 1951).
R14_____ Unanothorianite-bearing parapyroxenite, Malagasy Rebuplic, approximated from Roubault (1956), and Lenoble and Gangloff (1958).
V1______ Steenkampskraal, Van Rhynsdorp district, South Africa (Pike, 1958).
V2______ Morro de Ferro, Brazil, higher grade portion, assuming 5-m depth (Wedow, 1961).
V3______ Morro de Ferro, Brazil, total to depth of 30 m, including lower grade halo around V2 (Wedow, 1961).
V4______ Agnew Lake (Canadium Thorium Corp.) deposit, Ontario (Thompson, 1960),
V5______ Higher grade vein deposits, Powderhorn district, Colorado.
V6______ Nigerian crude tin ore expected to be mined in 20-year period (Davidson, 1956a).
V7______ Veins exceeding 0.3 percent ThO_2, Wet Mountains, Colo., to 50-ft depth (M. R. Brock, written commun., 1962).

[1] Estimated to 1,000-ft depth.

In granitic rocks a significantly high proportion of the thorium has been found to be in the interstitial material that is soluble in HCl (for example, see Larsen, 1957, p. 251). In one laboratory study reported by Larsen, from 20.4 to 91.0 percent of the thorium in 16 samples of syenite, granite, granodiorite, quartz monzonite, and other rocks from the Front Range, Colo., is leachable. Leaching with HCI dissolved from each of the 16 samples a higher proportion of the thorium present than of the uranium. The Th : U ratio is therefore higher in the

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V8------ Veins exceeding 0.1 percent ThO_2, Wet Mountains, Colo., to 50-ft depth (M. R. Brock, written commun., 1962).
V9------ Pegmatite, Locality A, Bear Mountain, N.Y. (McKeown, 1951).
V10----- Reserves in vein deposits containing 0.5 percent ThO_2, Lemhi Pass, Idaho-Montana (U.S. Atomic Energy Commission, 1962).
S1------ Blind River uranium deposits, Ontario (Griffith, 1960).
S2------ Higher grade parts of Goodrich Quartzite, Palmer, Mich., approximated from Vickers (1956a).
S3------ 82 Cretaceous black-sand deposits, Colorado, Wyoming, Utah, New Mexico (Dow and Batty, 1961).
S4------ 33 Cretaceous black-sand deposits, New Mexico (Dow and Batty, 1961).
S5------ 19 Cretaceous black-sand deposits, Wyoming (Dow and Batty, 1961).
S6------ 16 Cretaceous black-sand deposits, Utah (Dow and Batty, 1961).
S7------ Conglomerate at Bald Mountain, Wyoming, explored portion (Borrowman and Rosenbaum, 1962).
S8------ Conglomerate at Bald Mountain, Wyoming, high-grade stratum (Borrowman and Rosenbaum, 1962).
P1------ Placer deposits, southwestern coast of India (Mahadevan and others, 1958).
P2------ Inland placer deposits of Bihar and West Bengal, India, approximated from Bhola and others (1958), and Shirke and Chatterji (1958).
P3------ Placers, all of Brazil. Grade uncertain and is approximated from Davidson, 1956a).
P4------ Placers, Pulmoddai Beach, Ceylon, calculated from Davidson (1956a).
P5------ Small headwater placers, southeastern Piedmont, U.S. (Overstreet and others, 1959).
P6------ Total for 84 flood plains, southeastern Piedmont, U.S. (Overstreet and others, 1959).
P7------ Total for all southeastern Piedmont, U.S., placers studied by Overstreet and others (1959).
P8------ Total of 13 placers, southeastern Piedmont, U.S. (Eilertson and Lamb, 1956).
P9------ Placer, Rabun Creek, S.C. (Hansen and Caldwell, 1955).
P10----- Placer, Hollow Creek, S.C. (Kline, Griffith, and Hansen, 1954).
P11----- Placer, Knob Creek, N.C. (Griffith and Overstreet, 1953b).
P12----- Placer, First Broad River, N.C. (Hansen and Cuppels, 1954).
P13----- Placer, Silver Creek, N.C. (Hansen and White, 1954).
P14----- Placer, South Muddy Creek, N.C. (Hansen and White, 1954).
P15----- Beach placer, Hilton Head Island, S.C. (McCauley, 1960).
P16----- Bauxite, Arkansas; Th content given by Adams and Weaver (1958) assumed to be applicable to bauxite reserves estimated by Gordon and others (1959).
P17----- Total for 8 placer deposits in Idaho and 1 in Montana (Eilertson and Lamb, 1956).
P18----- Placer, Bear Valley, Idaho (Kline and others, 1953).
P19----- Placer, Corral Creek, Idaho (Kline and others, 1955).
P20----- Placer, Big Creek, Idaho (Kline and others, 1951a).
P21----- Placer, Pearsol Creek, Idaho (Kline and Carlson, 1954).
P22----- Uranothorite placer, Camp Creek, Idaho (Robertson and Storch, 1955).
P23----- Placer, Scott Valley, Idaho (Kline and others, 1951b).
P24----- Placer, Rock Creek, Idaho (Robertson and Storch, 1955b).
P25----- 3 placer deposits in Lee and Burleson Counties, Tex. (Hahn and others, 1961).
P26----- Beach sands, Egypt, higher grade (Higazy and Naguib, 1958).
P27----- Beach sands, Egypt, lower grade (Higazy and Naguib, 1958).

interstitial soluble material than in the resistant accessory minerals of these rocks.

U.S. Geological Survey studies of thorium and uranium contents of igneous rock series (David Gottfried, written communication, 1962) are yielding information on areas and rock types that are low in amounts of these elements and are, therefore, unlikely places for thorium deposits. For example, 30 samples of basalt and andesite from 6 islands in the Marianas Arc range in thorium content from 0.4 to 2.4 ppm and in uranium from 0.09 to 1.5 ppm, significantly lower than similar rocks from other tectonic settings. Chemically these rocks are distinguished by high content of Al_2O_3 and extremely low content of K_2O. Volcanic rocks from the Pacific Northwest having similar chemical characteristics also have unusually low Th contents.

METAMORPHIC ROCKS

Thorium-rich zones in metamorphic rocks are known in many parts of the world, but specific information on size and grade is scarce. Many of the zones are migmatitic, pegmatitic, or biotite-rich, and contain monazite, thorite, uranothorite, allanite, xenotime, or brannerite. Such zones in the United States include those at Worcester and Southbridge, Worcester County, Mass. (Johnson, 1951); Passaic County, N.J. (Markewicz and others, 1957); San Bernardino and Riverside Counties, Calif. (Walker and others, 1956); Central City, Colo. (Young and Sims, 1961); Mesquite, Nev.; and Culpeper and Albemarle Counties, Va. (Stow, 1955). Similar zones in many parts of the world have been described. (For example, see Bowie and others, 1955; Davidson, 1956a; Mawdsley, 1958.)

Total resources of thorium in low concentrations in metamorphic rocks cannot be estimated but they probably are large. For example, some monazite-rich zones in lateritic granite gneiss, such as those in Sierra Leone described by Bowie and others (1955), may be as much as 1 mile wide and 10 to 20 miles long. The average ThO_2 content of a zone of this size is not known, but if it were as much as 100 ppm, 50,000 tons of ThO_2 may be present above a depth of 20 feet.

One of the largest thorium-bearing zones in metamorphic rocks, as described by Davidson (1956a), is a garnet-biotite schist zone about 100 feet wide and nearly 1 mile long in a belt in which pegmatitic rock is associated in Kerala, India. Davidson estimated that this zone possibly contained 100 to 200 tons ThO_2 per foot of depth. Five grab samples of richer ore averaged 17.9 percent monazite, which contains 10.7 percent ThO_2. These data suggest that potential thorium resources in deposits of this type may be large.

Rocks of the charnockite series occupy the southwestern part of Ceylon, and all the acid members of the series contain accessory monazite which becomes especially common, possibly reconcentrated, in graphite-bearing shear zones (Coates, 1935, p. 138). Interlayered with the charnockite is sillimanite-garnet-orthoclase granulite that contains about 0.1 pound of thorium-rich monazite per cubic yard (Imperial Institute, 1916, p. 353).

Northwest of Fort-Dauphin, Malagasy Republic, uranothorianite occurs in veinlike bodies of calcite, phlogopite, and anorthite, and in masses of disseminated grains in and closely associated with metasedimentary pyroxenite masses and lenses interlayered in Precambrian schist. The deposits have been described by Roubault (1956) and Lenoble and Gangloff (1958). About 100 of these deposits are reported to be from a few hundred to more than 150,000 tons in size, and to contain 0.1 to 0.6 percent uranothorianite. Reserves in the region of Mandrare are said to be about 2,000 tons of uranothorianite (Roubault, 1956). Lentils in the pyroxenite masses contain monazite, which locally makes up as much as 30 percent of the lentil, and apatite. The mineralized lentils are commonly masked by eluvium; therefore their size has not been well defined (Roche and others, 1956, p. 154–156). Because the mineral composition of the monazite-apatite lentils resembles that of the great vein deposit at Steenkampskraal in South Africa, considerable search has been made in the southeastern part of the Malagasy Republic for large monazite-apatite deposits, but none had been found as of 1960. Thorianite deposits like those in the Malagasy Republic have not been found in the United States. A favorable geologic setting in which to search for this type of deposit is that of pyroxenite and other metasedimentary rocks formed by high-grade metamorphism in the granulite facies.

Considerable reserves of thorium in metamorphic rocks are known in North Africa (Gangloff, 1959), but to the present (1964) they have not been exploited. In the Federation of Rhodesia and Nyasaland, accessory monazite is disseminated in quartz-feldspar granulite near Dedza, in garnetiferous biotite-quartz gneiss near Masamba, and in epidotized bands of gneiss north of Zomba (McNaughton, 1958a, p. 26; 1959, p. 47).

Less common types of thorium occurrences in metamorphic rocks are the allanite- and parisite-bearing contact-metamorphic zone at Nixon Fork, Alaska (Bates and Wedow, 1953), and the low-thorium monazite occurrences in carbonate-rock layers in metamorphic rocks in the Mineral Hill district, Idaho (Abbott, 1954; Anderson, 1958), which may be related to carbonatite. Low-thorium monazite is disseminated with apatite in corundum-mica schist in the Flinders Range, South Australia (Mawson, 1916, p. 263–264).

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EPIGENETIC DEPOSITS

Thorium-bearing veins in several areas in the Western United States have been known since 1949 and are among the important reserves of low cost thorium ore in the United States. In these veins the thorium minerals of greatest economic interest are thorite and thorogummite, but in veins elsewhere in the world other minerals, such as monazite, are also important. Common associates of the thorium and rare-earth minerals in many of these veins are quartz, carbonates, barite, fluorite, hematite, goethite, and pyrite.

Typical high-grade thorium veins range in thickness from a fraction of an inch to more than 20 feet and contain several tenths percent thoria and generally similar amounts of rare-earth oxides. Selected samples contain from 1 to 6 percent or more ThO_2. One of the richest veins is the unique Steenkampskraal monazite vein in South Africa, in which 7,500 to 15,000 tons of thorium is contained in ore of about 3- to 6-percent thorium grade (Pike, 1958.) This vein is 60 to 75 percent monazite, and it contains quartz, apatite, and other minerals; it is about 900 feet long and in most places is 2 to 6 feet thick. From 1953 to 1959, the Steenkampskraal deposit was a major source of the world's thorium production.

In the Letıtia Lake area, Labrador, low-grade niobium-thorium-rare-earth deposits are related to intrusions of alkali syenite into schistose, porphyritic volcanic and sedimentary rocks (Brummer and Mann, 1961). The radioactive zone is along a complex of amphibolite and albite bands, representing a shear zone, and is at least 1,800 feet long and 500 feet wide. Radioactive minerals were identified as allanite and monazite, and grab samples yielded 0.44 to 2.30 percent ThO_2 (Brummer, 1960). A similar zone more than 8,000 feet long was found 2¾ miles along the strike of the shear zone to the west.

Lodes and veinlike segregations of monazite occur in granite north of Fort-Dauphin in the extreme southeastern part of the Malagasy Republic. Locally the veinlike segregations are high grade, containing thoria-rich monazite, but they are small and therefore are not economic sources of monazite (Besairie, 1948, p. 120; 1953, p. 146; Lecoq, 1957, p. 592). Other examples of similar hard-rock deposits are the scattered disseminations and small veins of monazite, thorite, and davidite in Precambrian gneiss and schist at Thackaringa, Broken Hill district, New South Wales, Australia (Rayner, 1955, p. 62–69).

The principal areas of thorium-bearing veins and other hard-rock deposits in the United States are shown by Olson and Adams (1962). A comparison of this map with the geologic map of the United States shows the close association of deposits of this type with the areas of igneous and metamorphic rocks. The principal districts are in areas of Precambrian rocks. The deposits are also commonly associated with alkalic igneous rocks, as in the Powderhorn, Wet Mountains, and St. Peters Dome districts in Colorado, and Mountain Pass, Calif. In the Lemhi Pass district, Idaho, however, alkalic rocks have not been found, and genetic relationships of the veins are obscure.

The known thorium veins that appear to have the greatest potential are in the Lemhi Pass district in Idaho and Montana and in the Wet Mountains, Colo. Other districts that have produced small quantities of thorium from vein or replacement bodies, or contain promising deposits, include Powderhorn and St. Peters Dome, Colo.: Bokan Mountain, Alaska; Porthill, Idaho; and Mountain Pass, Calif. Districts containing thorium veins of uncertain, perhaps small, potentialities include San Bernardino and Riverside Counties, Calif.; Mineral Hill, Idaho; Duck Creek Pass, Deer Creek, and Bearpaw Mountains, Mont.; Salmon Bay, Alaska; Bear Lodge Mountains, Wyo.; Virgin Mountains and Cottonwood, Ariz.; Capitan Mountains, Gallinas Mountains, and Chico Hills, N. Mex.; Magnet Cove, Ark.; Wausau, Wis.; Hicks Dome, Ill.; and Easton, Penn.–N.J. Districts from which thorium minerals have been or might be obtained as a byproduct of other hard-rock mining include Dover, N.J., Mineville, N.Y., and Climax, Colo.

Because of the present limited demand for thorium, exploration of veins has been directed toward finding veins with several tenths percent ThO_2 or more. In general, the lower grade vein material, containing less than 0.1 percent, has not been evaluated, but the total amount of thorium in veins of grade 0.03 to 0.1 percent ThO_2 would add significantly to our total thorium resources. In the Wet Mountains, Colo., for example, numerous broad zones of potassium feldspar produced by hydrothermal alteration, associated with the thorium-rich veins, contain more than 300 ppm Th (M. R. Brock, written commun., 1962). Similar low-grade veins occur in the Powderhorn district, Colorado.

PLACER AND RESIDUAL DEPOSITS

NORTH AMERICA

In the United States, monazite-bearing placers are found in all Western States, in the Southeastern States and in Alaska. The deposits of greatest potential are in Idaho, Montana, North and South Carolina, Georgia, and Florida.

Placers in the Carolinas supplied all United States monazite during 1893–1909. The Carolina Piedmont placers are richest near the headwaters of the streams; the placers become larger downstream but are leaner because of admixture of monazite-free material from other tributaries (Mertie, 1953; Overstreet and others, 1956). One placer deposit on Horse Creek near Aiken, S.C., was dredged during the middle 1950's for rutile, ilmenite, monazite, zircon, and staurolite, but operations ceased in March 1958 (U.S. Bureau of Mines, 1959, v. 3, p. 894). This deposit was formed when the Cretaceous sedimentary rocks, in which the heavy minerals had previously been concentrated, were eroded and the heavy minerals were reconcentrated in the fluviatile placer deposit. The deposit on Horse Creek was thought by Perry (1957, p. 4) to be matched in size and quality by deposits along Shaw Creek and the South Fork Edisto River in northeastern Aiken County, S.C., but these placers have not been fully explored. Guillou and Schmidt (1960, p. B120) noted that the rocks in the Coastal Plain adjacent to the Horse Creek placer are less radioactive than Coastal Plain sediments in other nearby parts of northeastern Aiken County and Lexington County, S.C.; this relation suggests that the more radioactive areas may also be favorable for placers.

Monazite has been found in beaches along the Atlantic Coast from the Carolinas to the tip of Florida and on the Gulf Coast, particularly in Louisiana, Mississippi, and Alabama shores. Beach sands or raised beaches are being mined at Jacksonville and Trail Ridge, Fla., and other monazite-bearing beach sands have been developed along the Atlantic and Gulf Coasts. The Florida beach sand deposits contain only about 4 percent heavy minerals, of which only a fraction of a percent is monazite, and are considerably leaner in heavy minerals and in monazite than those mined elsewhere in the world. Beach sands along the Atlantic Coast of the Carolinas and Georgia have been explored by the U.S. Bureau of Mines and by others, and some black-sand deposits were found from which monazite could be produced in conjunction with other heavy minerals.

In Idaho, placer mining for monazite began on a small scale about 1903 and continued to 1910 (Santmyers, 1930, p. 15). After a lapse of nearly 40 years, mining resumed about 1948. The monazite content is greatest in placers derived from weathered quartz monzonite in parts of the Idaho batholith that were not glaciated during Pleistocene time. The thoria content of the Idaho monazite, somewhat lower than that of most commercial monazite, commonly ranges from 3.2 to 4.8 percent ThO_2, and rarely reaches 6 percent (Kauffman and Baber, 1956, p. 6). In addition to monazite in placer deposits in the Cascade, Boise Basin, and other regions in Idaho, radioactive black minerals—such as euxenite in the deposits in Bear Valley and uranothorite in the Hailey area—are very important (Mackin and Schmidt, 1956). Under the same economic conditions prevailing in 1952, when the price of monazite was about \$350–\$375 per ton, a deposit in Idaho may be economically dredged if it has a monazite content of 1 lb per cubic yard, provided all other conditions are ideal for dredging operations (Kline, 1952).

SOUTH AMERICA

Brazil's production of thorium minerals, second only to that of India, has been from beach sands, along 1,000 miles of coastline, that were formed chiefly by reworking of the Cretaceous and lower Tertiary sedimentary rocks by Recent wave action. The coastal area has undergone repeated emergence and submergence, and some of the largest reserves are in elevated beaches and bars behind the present coastline (Gillson, 1950). The content of heavy minerals in Brazilian black sands is reported to be 20 to 40 percent, of which 2 to 5 percent is monazite (Davidson, 1956a). The monazite contains 5 to 6 percent ThO_2. Reserves of monazite along the coast of Rio de Janeiro, Espirito Santo, and Bahia were estimated by Leonardos (1950, p. 137) to be at least 100,000 to 150,000 tons, and the total reserves in Brazil are very conservatively estimated to be about several hundred thousand tons (Davidson, 1956a). Individual deposits are commonly about 10 to 40 feet wide, 6 to 12 feet thick, and 75 feet to as much as 2 miles long. Placer deposits are also known along streams, but in general they are thought to be small compared to the beach-sand deposits. Attempts have been made to mine monazite from river sand in the interior of Sao Paulo, but the mining was abandoned because the raw sand contained only 2 percent or less monazite (Gottsschalk, 1915, p. 903).

In Uruguay, black sands on the beaches contain ilmenite and small amounts of monazite. The richest concentrates are from beaches 25 miles east of Montevideo. Monazite has been reported in beach and stream placers in Argentina, and in 1961 it was stated (Engineering and Mining Journal, 1962, p. 112) that 30 million tons of sand containing 4 percent monazite had been found in Cordoba Province, but the nature of the occurrence was not described and the deposits are not known to be minable under present technology.

Some mining companies were reported in 1956 (Mining World, 1956, p. 68) to be investigating monazite placers near the boundary between British Guiana and Brazil, but no monazite had been produced in British Guiana as of 1958. Monazite is a possible accessory mineral in fluvio-marine gold placers on the Isla de Chiloe, Chile (Falke, 1936, p. 588).

AFRICA

Monazite is present in many parts of Africa, and it is likely that monazite-bearing placers will be found in many more areas than are now known.

In South Africa, beach placers on the Natal coast contain from 5 to 90 percent heavy minerals in the raw sand, but monazite rarely constitutes more than 1 percent of the concentrate (Partridge, 1939, p. 175; Kent, 1939, p. 31–36). Fluvial sands of the Breede River, Cape of Good Hope Province, contain detrital monazite (Coppenhagen, 1945, p. 153–157). The banks of the Sandspruit about 8 miles south of Steynsdorp in the Transvaal have been reported to have a little detrital monazite, and nearby, possibly in the Swaziland Protectorate, about 3.5 tons of monazite was recovered in the Oshoek tinfields prior to 1918 (Hall, 1918, p. 309, 316). The output referred to the Oshoek tinfields may be the same as that credited to the cassiterite placers at Mbabane, Swaziland Protectorate (Bond, 1930, p. 342). The alluvial monazite of the Mbabane tinfields is regarded as being of no economic importance. Although no production has been reported through 1962 in Mozambique, monazite containing 5 percent ThO_2 makes up as much as 1 percent of the black-sand deposits at Marracuene (Davidson, 1956a). Other monazite-bearing sands occur at the mouth of the River Rovuma.

In Rhodesia, monazite and thorite, rarely in amounts as high as 2 lbs monazite per cubic yard, are present in the alluvium of some rivers, but no production has been reported. Widespread occurrences of detrital monazite in the streams in Nyasaland were noted as early as 1906, but none was an economic source for the mineral (Dunstan, 1908, p. 10–35). Concentrates from streams at 70 localities in areas underlain by crystalline rocks in southern Nyasaland are monazite-bearing (Dixey, 1930, p. 11). Of 40 samples of river sand studied in the Tambani region, Nyasaland, according to Davidson (1956c, p. 207–209), thorium-bearing minerals were found in the following number of samples: monazite, 39; thorite, 25; pyrochlore and (or) betafite, 25; uranothorianite, 11. Beach placers along the shores of Monkey Bay and elsewhere around Lake Nyasa contain monazite. The Lake Nyasa beaches were being prospected in 1957, but no deposits had been mined by 1958 (McNaughton, 1958b, p. 28).

In the Central African Republic, monazite containing 6 percent ThO_2 occurs in diamond-bearing concentrates from the Cheniandaka River (Brustier, 1934, p. 435), and detrital monazite containing 7 percent ThO_2 has been reported from Jakundu (Marble, 1949b, p. 90). Some of the Tertiary sedimentary rocks of Tanganyika are monazite-rich (Davidson, 1956a), and workable placers may be discovered, especially where reconcentration might occur by erosion of these rocks. The presence of monazite in the coastal Tertiary sedimentary rocks indicates a far more general distribution of monazite in Tanganyika than the few known occurrences show. The highly metamorphosed rocks of the basement system and migmatite and gneissose granite developed from them underlie 70 percent of the area of the country. Surficial mantle, fan detritus, fluvial sediments, and lake deposits derived from these plutonic rocks are likely to contain monazite. Monazite is widely distributed in the gold placers in the Uganda Protectorate, but some is low in ThO_2 (Wayland, 1933, p. 21–22; Marble, 1949b, p. 91), and it has not been recovered economically. Black sand at the mouths of the Galana and Tana Rivers on the Indian Ocean coast of Kenya (Pulfrey, 1948, p. 297; 1954, p. 25) and along the coast of Patta Island near the border between Kenya and the Somali Republic (Hintze, 1922, p. 344) contains minor amounts of monazite.

In the Somali Republic, ilmenite sand containing 0.06 percent monazite is concentrated on the seaward side of a belt of coastal dunes near the mouth of the Guiba River (Mining Journal, 1915, p. 759; Holmes, 1954, p. 66). The amount of monazite is too small to be recovered economically at the present time.

In Ruanda-Urundi in the valleys of the Rukarara, Binana, Ruyobora, and Agafugoto Rivers, monazite placers of undescribed size are known (Fontainas and Ansotte, 1932, p. 25; Congo Belge Bull. Officiel, 1933, p. 517, 524, 527; Miller, 1939, p. 9).

Placer monazite has been found in gold- or cassiterite-bearing streams in many parts of the Republic of the Congo, particularly the northeastern part (Corin, 1931, p. 151; Congo Belge Bull. Officiel, 1926a, p. 489–493; 1926b, p. 788, 790). A small tonnage of monazite was produced in the Republic of the Congo from 1951 through 1956 (table 1), but the source is not known.

In Nigeria, both monazite and thorite occur in tin and columbite concentrates, and could be recovered if prices were sufficiently high. Concentrates containing thorite, zircon, and monazite were exported in 1956, 1957, and 1958 for their thorium content (Parker, 1962, p. 56). Davidson (1956b) reported that 75 tons of thoria, in crude tin ore averaging 0.4 per cent equivalent thoria, annually passes through Nigerian tin sheds, and that reserves of 1,000 to 2,000 tons thoria are in the crude tin ore that is likely to be mined over a 20-year period. Thorite is more important than monazite as a source of thorium in Nigerian tin placers. Slags from British tin smelters, which treat a mixture of Bolivian and Nigerian ores, were reported by Davidson (1956a) to contain about 0.1–0.2 percent ThO_2.

Small amounts of monazite were reported in streams in the Republic of Cameroun (Tattam, 1938, p. 8–9; Marble, 1949a, p. 37; Miller, 1939, p. 10; Wright and others, 1938, p. 68), in placers near Beyla, Republic of Guinea (Echo des Mines et de la Metall., 1935, p. 178–179), and in sands of the Casamance River in the Republic of Senegal (Miller, 1939, p. 10; Wright and others, 1938, p. 68).

The sand bars and beaches on the Sierra Leone coast, which have been investigated for titanium minerals, very likely contain considerable amounts of monazite, derived from erosion of monazite-bearing migmatite. Many streams in the interior have been cited as monazite-bearing, but workable placers have not been found (Dixey, 1954, p. 74; Holmes and Cahen, 1955, p. 29–30; Junner, 1929, p. 5–11). Monazite in low concentrations has been found in stream gravels at many places in Ghana, but it is not known to be abundant enough to form workable deposits or to be recovered from gold or diamond placers (Kitson and Felton, 1930, p. 13–48; Junner, 1943, p. 21).

Beach and dune sands between Port-Etienne and Saint-Louis on the Atlantic coast of the Mauritanian Islamic Republic locally contain monazite (Dropsy, 1943, p. 251–263). The dominant heavy mineral is ilmenite at the few examined localities along this long coast. Monazite is generally sparse, but it probably could be recovered as a byproduct if the ilmenite were mined.

In Egypt, a little monazite has been produced from placers of the Nile River delta, and resources, including low-grade material, have been estimated to be about 200,000 tons of monazite (Higazy and Naguib, 1958). Inasmuch as a large part of the heavy minerals annually transported by the Nile to its mouths originate on the Abyssinian Plateau, the Aswan High Dam may ultimately slow or halt this transport. Minor detrital monazite occurs in the sediments of the Dacata River at Errer, Ethiopia (Usoni, 1952, p. 70).

The Malagasy Republic produced 1.6 tons of monazite, as a byproduct of gold mining of the stream placers, in 1923 (Turner, 1928, p. 82), and exported 1.3 tons of euxenite and monazite in the first quarter of 1924 (Madagascar Director of Mines, 1924, p. 139).

Beach sands in southeastern Malagasy Republic were first mined in 1954, and monazite was produced at least through 1962 (table 1; see also Lecoq, 1957, p. 591). Monazite-bearing marine sand forms a belt 1,000 to 5,000 feet wide along the southeastern coast of the Malagasy Republic, and in the vicinity of Fort-Dauphin the sand extends inland for several miles (Roche and others, 1956, p. 147–152). The present beaches are 35 to 160 feet wide and locally contain very rich concentrations of monazite. Inland from the present beaches are old raised beaches, and further inland are modern and old dunes. A barren overburden buries rich monazite placers in the old beaches. The modern dunes constitute large-volume, low-tenor monazite placers, and the old dunes large-volume, intermediate-tenor placers. Placers in the old dunes are less rich than those in the beaches, but they contain 25 to 30 percent of heavy minerals including 1.2 to 1.5 percent monazite. More than 80 percent of the known reserves of monazite along the southeastern coast are in the old dunes. South of the Mananara

River, 11 explored beaches contain an estimated 3,000 tons of monazite, and 16 old beach and dune deposits 35,000 tons of monazite, which contains 5.3 to 9 percent ThO_2 (Roche and others, 1956, p. 151–153).

EUROPE

For many years the beach placers on the Galician coast of northwestern Spain annually yielded small quantities (about 20 tons) of monazite containing about 5.6 percent ThO_2 (Davidson, 1956a).

Beach sands along the Tyrrhenian coast of Italy were reported by Ippolito (1956) to contain uraniferous thorite, monazite, and a new thorium-bearing mineral, perrierite. The total black-sand deposit above sea level has been estimated to consist of 444,000 tons containing 710 tons of thorium-bearing minerals, which average 3.5 percent ThO_2, or 27 tons (60 ppm) ThO_2 (Ippolito, 1956). Because perrierite appears to be associated with rhyolitic lava, the possibility exists that elsewhere in the world similar lava that is thoroughly weathered may be the source of detrital perrierite.

U.S.S.R.

Numerous placer occurrences of monazite are known in the U.S.S.R., but none are known to be extensive or productive, although monazite is probably recovered as a byproduct of gold dredging in some areas. Some of the potential placer areas are the Alichur Valley in the Pamir Range of Tadzhikistan, the shores along Lake Baikal, the Yenisei and Lena Rivers, the gold-producing areas of the northern Ural Mountains, the Altai-Sayan Mountains, and some of the streams in Transbaikal and eastern Siberia. According to Davidson (1956a), monazite and thorite may be present in the titanomagnetite-bearing black sand between Batum and Gagry on the Georgian coast of the Black Sea. The reserves of black sand in this area have been estimated at about 10 million tons.

ASIA

Beach placers on the west coast of India have been the world's principal source of monazite, owing to a combination of monazite-bearing source rocks, deep lateritic weathering, initial concentration in coastal sandstones, and natural sorting of the heavy minerals accumulated in beach sands. During the monsoon season, when greatest concentration is accomplished, the minable sands contain 40 to 95 percent heavy minerals. Monazite makes up from less than 1 to about 2 percent of the ilmenitic black sand. Because of its abundance, Indian monazite has even been considered as a possible source of phosphate for fertilizer (Kartha, 1955, p. 53; Nair and Moosath, 1955, p. 63). Monazite was discovered here in 1909, and a few hundred to 5,200 tons per year was

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exported during 1911–45, after which the export of fissionable material was prohibited.

Principal deposits are in Kerala, but smaller deposits are also known on the west coast as far north as the mouth of the Narbada River. Recently discovered deposits on the east coast are of lower tenor but larger size than those on the west coast, and probably contain a greater total amount of monazite. Reserves of monazite in the Kerala–Cochin sector of the west coast have been estimated by Wadia (1956) as a little more than a million tons. In this deposit and others on Indian beaches, Wadia estimated, probably very conservatively, the following thorium reserves:

1. 150,000 to 180,000 tons in monazite sand, easily and economically extractable.
2. A smaller tonnage from less concentrated deposits scattered in beach and dune sands and on the beds of lagoons and stream courses.

In the Ranchi and Purulia districts in Bihar and West Bengal, large alluvial deposits of monazite were found in the late 1950's which add greatly to the thorium resources of India (Bhola and others, 1958; Shirke and Chatterji, 1958). Small amounts of monazite occur in sandstone intercalated in the Deccan flows. Streams in the charnockite areas of the Kadur and Hassan districts, Mysore, were widely prospected for monazite in 1916–17, and small amounts were found at many places, but no workable deposits were discovered (Memminger, 1917, p. 681). Streams reaching the coast of Andhra Pradesh from the Waltair Highlands are monazite-bearing (Mahadevan and Sathapathi, 1948, p. 297).

The interesting possibility, apparently as yet unexplored, exists that in the Gulf of Mannar area, shallow-water deposits along Adams Bridge between India and Ceylon may contain monazite. Beach placers are present on opposite shores of the Gulf. Currents setting northeastward through the Gulf may effect along-shore transport of monazite and concentrate it, as a great natural riffle, on the beaches near and in the shallow water in the Adams Bridge area.

Ceylon has produced several hundred tons of monazite from beach deposits and a few tons of thorianite from stream placers and decomposed pegmatite. Several small monazite-rich beaches on the west coast produced monazite in the early 1920's. A deposit of at least 3 million tons in northeastern Ceylon, at Pulmoddai, contains 72 percent ilmenite, 18 percent zircon and rutile, and 0.3 to 0.4 percent monazite (Davidson, 1956a). Ceylon monazite contains about 9 percent ThO_2. Small deposits of thorianite and thorite, which are recovered in gem mining, occur in interior Ceylon in stream gravels.

The sources of these minerals are decomposed gneiss, pegmatite, and other granitic rocks. The principal deposits are in the Ratnapura district, but several other districts also contain these minerals in stream placers.

In Pakistan, no economic deposits of monazite had been found as late as 1959 though isolated occurrences of this mineral had been reported from the Indus and Hunza Rivers in West Pakistan (Danilchik and others, 1959, p. 5). In 1962 radioactive beach sand was reported to occur intermittently for 100 miles between Chittagong and Teknaf on the Bay of Bengal, East Pakistan (Schmidt and Asad, 1962). Apparently the monazite is accompanied by radioactive black minerals, and the monazite alone accounts for less than half of the total radioactivity. The placers, which have not been fully appraised, are tens to hundreds of feet wide, hundreds to thousands of feet long, and as much as several feet thick.

A concentrate from alluvium of the Brahmaputra (Tsangpo) River near Chaksam in southeastern Tibet is reported to contain monazite (LaTouche, 1918, p. 390).

The placer tin deposits of the Malay Peninsula (Fermor, 1940, 1950; Harris and Willbourn, 1940), Burma, and Thailand contain considerable monazite but generally it has not been recovered in the tin mining. Monazite rarely makes up as much as 50 percent of the heavy sands at Kuala Trengganu on the east side of Malaya (Engineering and Mining Journal, 1906). Malayan monazite resources probably are greater than those of Burma, Thailand, or Indonesia. Malayan monazite contains 3.4 to 9.4 percent ThO_2 and is therefore a richer source for thorium than the Indonesian mineral. It is likely that 100 to 200 tons of ThO_2 passes through Malayan tin-concentrating plants annually (Davidson, 1956a). A small amount of monazite is reputed to have been produced in 1914 at Sungei Badang in the Gambang placer tin field in Pahang (Fitch, 1952, p. 111), and about 1930 some mixed concentrates containing monazite were shipped. During 1944 and 1945 the Japanese in Malaya produced 220 tons of monazite and 200 tons of a mixed monazite-zircon concentrate from cassiterite tailings (Fermor, 1950, table 2). In the Ulu Sempan area of Pahang, Malaya, placer concentrates contain columbite and monazite (Scrivenor, 1907, p. 42). In the Puket-Pangnga region of Thailand, the tailings from tin mining also have uranium- and thorium-bearing niobates and titanates (Davidson, 1956a) such as euxenite and brannerite.

Placer concentrates from Wan Hpa-lan in the southern Shan States, Burma, contain abundant monazite (Chhibber, 1934, p. 240). Cassiterite placers in the Tavoy district have various amounts of monazite

(Heron, 1917, p. 180). Apparently unfounded reports early in 1948 stated that large deposits of thorium-bearing minerals had been discovered in central and eastern Burma (Engineering and Mining Journal, 1948a, b).

Monazite occurs along the coasts and in streams at many places in southern, eastern, and northeastern China. Economically valuable amounts of monazite are said to be associated with cassiterite in the tin placer district of southwestern Hunan Province and northeastern Kwangsi Province (Peng, 1947, p. 111–115). The placer monazite is derived from cassiterite-bearing granite that intrudes Carboniferous limestone and is unconformably overlain by Cretaceous sedimentary rocks (Hsieh, 1943, p. 82), a mode of occurrence that is suggestive of low-thoria monazite. Although detrital monazite has not been reported in the Cretaceous sedimentary rocks, it probably occurs there. Extensive heavy-mineral deposits, probably monazite-bearing, occur along the coast in southern Kwangtung Province, but details are lacking (Zenkovich, 1960, p. 355). The beaches of the coastal islands of Fukien Province and stream sand in Ho-pei Province contain detrital monazite, and beach placers are found along the coast of Shantung Province and Liaotung Peninsula (Wong, 1919, p. 215; Tsieh, 1926, p. 238–239). Monazite is also reported in Heilungkiang Province, Manchuria, near the Amur River. No evaluation of the mainland deposits has been presented, but probably the amount of monazite in the Hunan and Kwangsi tin districts is moderately large. The coastal areas probably have large low-tenor concentrations of detrital monazite more like those along the Atlantic coast of the United States than those of Brazil or India.

Monazite and thorite occur in stream and beach placers on Taiwan (Shen, 1956), and monazite in beach sands on Quemoy. One deposit in northwestern Taiwan is reported to contain 4.5 percent heavy minerals in the beach sand, of which 3.4 percent is monazite. Total Taiwan beach-sand reserves are estimated by Shen as 7,500,000 metric tons, from which 200,000 tons (2.7 percent) heavy sand containing 4.4 percent monazite can be recovered.

Monazite occurs in stream and beach placers in Korea, and is by no means rare in some of the richest gold-dredging ground in the country, where it is accompanied by allanite, xenotime, euxenite, fergusonite, and samarskite. Before 1942 these minerals received no attention, but from 1942 through 1945 many hundreds of tons of monazite was produced by hand methods. The valley of the Kum-gang alone yielded 2,200 tons of mixed zircon-monazite concentrate. Beginning in 1952 a variable but persistent output was achieved (table 1). The Korean First Five-Year Economic Plan, 1962–66, which uses 1960

(10 metric tons monazite produced) as a base year, gives the proposed monazite production in metric tons as: 1962, 300; 1963, 350; 1964, 400; 1965, 500; 1966, 600. Data on monazite reserves for several localities have been published. As estimated by Kim and others (1958, p. 169–170), five stream placers in Chŏlla-namdo contain 70,000 tons of monazite; stream placers at Munbaek-myŏn in Ch'ungch'ŏng-pukto contain 1,200 tons, and at Chŏnghowon-ŭp in Kyŏnggi-do, 18,700 tons. Beach placers on the coast of Kangwŏn-do, which are rich in ilmenite but lean in monazite, are conservatively estimated to contain 1,600 tons of monazite (Yoon and others, 1958, p. 206). There is much more monazite in Korea than these few figures on reserves suggest.

In Japan, thorium minerals occur in pegmatites and granitic rocks and in placers derived from both. Deposits are small and there has been no significant production, although in the Naegi district monazite- and thorite-bearing cassiterite deposits were mined on a small scale during World War II.

Indonesia has produced monazite as a byproduct of tin placers, principally on the islands of Singkep, Billiton, and Bangka off the east coast of Sumatra. Small but unrecorded amounts of monazite were shipped from Singkep, the largest monazite producer, in 1894–96, and 1,565 tons in 1936–40. Billiton produced smaller amounts in the years 1896 and 1909. Two samples of Singkep monazite assayed only 3.4 and 3.27 percent ThO_2 (Davidson, 1956a); the Billiton monazite is also low in thorium (Hintze, 1922, p. 342, 370). Indonesia achieved a sporadic production of monazite in the 1950's (table 1).

Monazite has also been reported in beach sands of Borneo, northern and western Sumatra, and in stream placers near Bengara, Borneo. Streams on the northern and northeastern flanks of Gunong Lesong in Sarawak are notably rich in monazite (Haile, 1952, p. 14; 1954, p. 35, 102; Wilford, 1953, p. 33). Monazite has been found in concentrates from the Sungei Entabai and from the delta of the Batang Rajang (Roe, 1958, p. 20–21). Marine black sand with small amounts of monazite extends along the Sarawak beach for 2¾ miles near the mouth of the Batang Bintulu, but the deposits are not economic sources for monazite (Wilford, 1953, p. 33). Small deposits of detrital monazite are known at three localities in North Borneo (Roe, 1958, p. 128).

In the Philippine Republic, radioactive stream and beach sands, some containing monazite, have been reported from 17 localities but have not been evaluated economically (Bacon, 1910, p. 277–278).

AUSTRALIA, NEW ZEALAND, AND ANTARCTICA

Small amounts of monazite have been reported from every State in Australia and from New Zealand. Monazite is produced (table 1) as a byproduct of the Australian beach-sand industry, which furnishes much of the world's zircon and rutile (Gardner, 1955). The heavy minerals occur in large deposits sporadically present from the mouth of the Johnstone River to Batemans Bay, New South Wales, in southern Queensland, and in western Australia. Monazite averages no more than 0.3 percent of the commercial heavy minerals, and contains an average of 6.6 percent ThO_2.

Small, or less well known, beach deposits occur at the Hey River estuary near Weipa Mission on the Gulf of Carpentaria, Queensland (Baker and Edwards, 1957, p. 1); Kangaroo Island, south Australia, where the monazite contains more than 8 percent ThO_2 (David and Browne, 1950, p. 317); the east coast of Tasmania and King Island between Tasmania and Victoria (Wylie, 1950, p. 165, Nye and Blake, 1938, p. 96); and the beaches of eastern and southern Victoria of which the leanest are the southern beaches. No doubt beach placers will be discovered elsewhere along the coasts of Australia.

Stream placers mined for cassiterite, wolframite, or gold contain monazite at many places in Queensland and New South Wales. Intermittent attempts have been made to market monazite from the cassiterite placers, but the efforts failed because of the low tenor in thoria. Monazite-bearing fluvial cassiterite placers are known in Queensland at Cairns, the Russell River, Walsh, Tinaroo, California Creek, Emu Creek, Nettle Creek, Bamford, Ord, Coolgara, and the Annan River (MacDonald 1912, p. 15; Dunstan, 1913, p. 733; Ball, 1915, p. 7; Saint-Smith, 1915, p. 556–557). Similar placers in New South Wales are at Vegetable Creek, Emmaville, Torrington, Deepwater, The Gulf, Black Swamp, and Stannum (Mingaye, 1909, p. 283; Carne, 1912, p. 91; Raggatt, 1925, p. 16; David and Browne, 1950, p. 316). In Tasmania, low-thoria monazite occurs in cassiterite placers on the Ringarooma River, in the Scottsdale district, the Forth River area, the Stanley River region, the North and South Heemskirk fields, Mount Bischoff, Mount Stormont, the Yellow Band Plains, and at the foot of the Meredith Range (Petterd, 1910, p. 121; Nye, 1925, p. 28; Reid, 1919, p. 47–48; Waterhouse, 1914, p. 113–114). Fluvial monazite localities in Victoria include the Bonang district, the Koetong area, the Mitta Mitta River southeast of Albury, Bethanga, the LaTrobe River, Stawell, and Nhill (Copland, 1905, p. 3–6; David and Brown, 1950, p. 316; Baker, 1959). Monazite is quite common in the cassiterite placers at Shaw, Cooglegong, Moolyella, and Greenbushes, Western Australia (Simpson, 1912 p. 94). It is also present in cassiterite-free alluvium from the Deep River and the Swan River.

Detrital minerals such as monazite, uranothorite, and allanite, have been found at various places in the stream gravels and beach sands of New Zealand, principally South Island and Stewart Island. The most frequently cited monazite occurrences are in the western and northwestern parts of South Island, particularly alluvial and fluvioglacial deposits in the basin of the Grey River and littoral and stream deposits along the coast from Cape Foulwind to Westport (Hutton, 1950, p. 697), but no deposits are known from which commercial production of rare earths and thorium is expected (Henderson, 1924, p. 14).

Along the coast of Antarctica ice-rafted detrital monazite has been reported in the beach sand of a small island about 110 miles north of Cape Royds and near vocanic Mount Erebus (Fitzau, 1909, p. 480). Trace amounts have been found between Cape Adare and Gaussberg (Mining and Engineering Review, 1911, p. 192). No large deposits are known.

SEDIMENTARY ROCKS

The thorium content of common sedimentary rocks is roughly about 5 ppm for sandstone (Joly, 1910), 10–12 ppm for clay and shale (Joly, 1910; Minami, 1935), and 1 ppm for limestone (Evans and Goodman, 1941). In sandstone and conglomerate much of the thorium is in heavy detrital minerals and, because these are unevenly distributed in the rock, the thorium content is variable. The thorium content of 46 samples of the Chattanooga Shale, which is abnormally rich in uranium, ranged from 8.1 to 15 ppm and averaged 10.8 ppm (Andrew Brown, written commun., 1962), approximately the average of many other common shales.

Abnormally large amounts of thorium, although uncommon in sedimentary rocks, are found chiefly in the following types of deposits:

1. Ancient placers.
2. Ancient conglomerates rich in thorium and uranium, such as the Blind River, Ontario, deposits, the origin of which has not been definitely determined.
3. Thorium-bearing dolomite, which is known in at least one area, the McLean Bay area of Great Slave Lake, Northwest Territories.

Ancient placers were formed by the same processes as the modern placers; the placers were subsequently buried by other sediments, were elevated in some places by tectonic movements, and were then exposed or made accessible by partial erosion of the overlying material. Several ancient placers have a rare-earth and thorium–minerals content that equals or exceeds that of the modern placers. Examples of ancient placers that contain abundant monazite are found in the Deadwood Formation of Cambrian age, Bald Mountain district, Sheridan County, Wyo.; the Goodrich Quartzite of Precambrian age in the Palmer area, Marquette County, Mich.; the Tuscaloosa Formation of Late Cretaceous age in the Southeastern Coastal Plain; and the black-sand concentrations in Upper Cretaceous sedimentary rocks in the Rocky Mountain region.

In the Bald Mountain district, Wyoming, detrital monazite is concentrated in an ancient placer deposit at Bald Mountain in the conglomerate near the base of the Deadwood Formation, overlying the Precambrian granite. At least 20 million tons of material averaging about 2.5 lb monazite per ton is present, and one high-grade stratum contains at least 675,000 tons averaging 13.2 lb per ton (Borrowman and Rosenbaum, 1962). The ThO_2 content of the monazite is 8.8 percent. This part of the Deadwood Formation in other places in northeastern Wyoming and in the Black Hills, S. Dak., has varied slight anomalous radioactivity. Although other deposits as rich as those in the Bald Mountain district may be present in the Deadwood Formation, this possibility is uncertain and unpredictable without more information than is now available.

Fossil placer monazite concentrations whose ThO_2 content is in the 15–30–ppm range probably occur in Cretaceous, Tertiary, and Quaternary sediments of the Atlantic and Gulf Coastal Plains. There is no information to indicate that fossil placers of this grade occur in the Gulf Coastal Plain below the unconformity between sediments of Quaternary and Tertiary age, but they possibly occur at and above that unconformity in the Gulf Coastal Plain. In the Atlantic Coastal Plain, fossil placers may be found at the unconformities between rocks of Quaternary and Tertiary age, of Tertiary and Cretaceous age, and of Cretaceous and Paleozoic or Precambrian age. Probably some fossil placers at these unconformities, particularly the lowest, are also in the >30–ppm grade.

In the Upper Cretaceous sandstone beds of Utah, Wyoming, New Mexico, and Colorado there are at least 82 black-sand deposits having a total ThO_2 content of 9,010 tons and an average grade of 0.03 percent ThO_2 (Dow and Batty, 1961). Detrital thorium-bearing minerals were concentrated in these beach-sand deposits by the sorting action of waves and currents along the shoreline of the regressive Cretaceous sea. Many additional similar black-sand deposits undoubtedly are present in unexposed parts of these formations. These undiscovered deposits probably contain at least several times the resources of the known deposits.

Detrital grains of monazite are abundant in the matrix of pebble conglomerate of the Goodrich Quartzite in the Palmer area, Michigan (Vickers, 1956a, 1956b). The monazite-rich rocks extend over an area about a mile long and half a mile wide. Sampling and radiometric surveys indicate an average monazite content of at least 2.9 lbs per ton, although some individual beds are considerably richer. A rough calculation using these figures indicates that a block 6,000 feet long, 850 feet thick, and 1,000 feet downdip may contain as much as 46,000 tons ThO_2 at a grade of 110 ppm. Within this block are higher-grade layers containing 10 lbs or more monazite per ton. The average grade of monazite-bearing quartzite that would be amenable to open-pit mining methods is not known, but Vickers (1956a) believed that large tonnages are available that would contain about 10 lbs of monazite per ton (about 370 ppm ThO_2). Additional exploration would be necessary to determine the amount and grade of monazite-bearing rock present.

The Goodrich Quartzite crops out over an area of several hundred square miles in northern Michigan, but the main concentrations of monazite have been found near Palmer in an area of about 3 square miles. About 12 miles southeast of Palmer small local concentrations of monazite have been found in an outlier of Goodrich Quartzite. Because monazite in the Goodrich Quartzite seems to be restricted to a small area, the mineral is believed to be derived from a local source (Vickers, 1956a). Although there is considerable potential for the discovery of other concentrations like those at Palmer, such deposits are undoubtedly of local extent and represent only limited parts of the Precambrian quartzites of the region.

In other parts of the world, ancient placers have been found, particularly through exploration by radiation detection methods (for examples, see Nel, 1959; Gangloff, 1959; Davidson, 1951; Bowie and others, 1955; O'Brien, 1958; Ponsford, 1955), but very little quantitative data have been published regarding such occurrences.

In North America one of the greatest potential sources of thorium is in conglomerate in the Matinenda Formation in the Blind River district, Ontario, Canada (Roscoe, 1957; Griffith, 1963). The ratio of thorium to uranium ranges mostly from 3:1 to 1:4. The uranium deposits average about 1 part ThO_2 for 2 parts U_3O_8; an annual production rate of 13,000 tons of U_3O_8 might yield from 5,000 to 6,000 tons of ThO_2 (U.S. Atomic Energy Commission, 1959), about 10 times the present thorium production of the world. The Rio Tinto Dow plant, which began operation in 1959, is designed to recover about 150–200 tons of thorium salts annually as a byproduct of uranium production.

The thorium in the Blind River deposits is largely contained in monazite, brannerite, and uraninite which, along with smaller amounts of thucholite, constitute the chief uranium ore minerals. The bulk of the thorium appears in the leach liquors from the uranium recovery process, from which it is obtainable at moderate cost.

If an average figure of 0.06 percent ThO_2 for the Blind River uranium ores is used, an estimated 200,000 tons of ThO_2 exists in the uranium deposits to a maximum depth of 3,700 feet. Estimates of the amount of high-thorium, low-uranium ore in the region have not been published, but the thorium reserves of the region may be significantly increased when data are available on ores that are low in uranium relative to thorium content.

Uraninite from the Rand, South Africa, has been reported to contain as much as 2.70 percent ThO_2 (Liebenberg, 1958), and monazite is also present in places. In the uranium- and gold-bearing reefs of Jacobina, Brazil, thorium has been reported in trace amounts (Bateman, 1958). In both the Rand and Jacobina, the proportion of thorium is much smaller than in the Blind River deposits and has not been recovered commercially.

Large uranium-thorium deposits similar to those at Blind River have not been found in the United States. Similar conglomerate beds of Precambrian or possible Paleozoic age in the United States may contain comparable deposits and thus have potential thorium and uranium resources of uncertain magnitude, but there is no basis on which a valid numerical estimate of this potential can be made. Considerable exploration of areas that seem favorable, on the basis of paleogeologic interpretations, probably will be required to find such deposits in this country.

Thorium-bearing dolomitic limestone at McLean Bay on the southeastern shore of Great Slave Lake, Northwest Territories, has been explored (Lang, 1952, p. 63–65). A zone of Precambrian dolomite that shows concentric structure of possible algal origin is stained with hematite and contains small quantities of thorium and uranium in the ratio of about 5 : 1. The deposits have been known for several years but apparently they have not been mined.

THORIUM RESOURCES

CATEGORIES

Many factors determine what constitutes recoverable resources. Among these are the grade or percentage of thorium, the mineralogic composition, the minimum size of deposit that may be exploitable, the location, and the proportion of the metal recoverable by the mining and milling methods employed. Economic and technologic developments have a strong influence on what constitutes ore and what is commercially recoverable. In order to achieve a common basis for resource estimates without regard to these variable factors, the thorium tonnage figures used in this report refer to the total thorium in the rock or deposit rather than the proportion that may ultimately be recoverable.

Resources of thorium may be divided into (1) identified or known resources, and (2) unidentified or undiscovered resources. Identified, or known, resources are those in areas known to contain amounts of thorium that can be estimated with reasonable assurance, and are defined to include both indicated and inferred ore in these areas. Unidentified or undiscovered resources include resources of the same grade or workability whose existence is surmised on the basis of geologic reasoning, but whose specific location is not known. This category allows for unexposed and undiscovered deposits occurring at depth in areas of known mineralization and also for districts and isolated occurrences yet to be found in environments similar to those of known occurrences. Total potential resources of thorium are the sum of the known and the undiscovered resources. The terms "measured," "indicated," and "inferred" are used with conventional meaning to describe the degree of certainty of estimates of reserves, although owing to inadequacy of exploration very little ore can be classed as measured or indicated; marginal and submarginal resources are not well enough explored to be classed as other than inferred.

All thorium in the earth's continental crust, about 11.4 ppm, totals about 10^{12} tons to a depth of 1,000 feet. A more realistic appraisal of resources, however, is attained by discriminating only those materials that are well above the background thorium content or might conceivably be exploitable at some future time. Categories of resource estimates used in this report are, in parts per million, $>$3,000, 300–3,000, and 30–300 for hard-rock deposits, and $>$15 and $<$15 for placer deposits. Although little if any thorium is now being mined in the United States, the U.S. Atomic Energy Commission has estimated that ThO_2 might be available at a price \$5 or less per pound from Lemhi Pass thorite ore having a grade of about 0.5 percent (U.S. Atomic Energy Commission, 1962). A concentration of 300 ppm ThO_2 is, with few exceptions, the approximate upper concentration limit of known igneous rock bodies of sufficient size to be quarried. Placer deposits containing more than 15 ppm ThO_2 in the sand might be exploitable in the United States if the price of thorium were about \$10 per pound. Lower grade categories are included as marginal and submarginal resources.

UNITED STATES

Estimates of thorium resources of the United States, by geologic occurrence and by grade, are given in table 3. Data on which fully reliable resource estimates can be made are not available, and the estimates shown in these tables, based on fragmentary information of varying degrees of reliability, will no doubt be revised, probably upward, as geologic mapping, exploration, and development proceed.

The resources listed in table 3 are divided into four geologic types and five grade categories, expressed in parts ThO_2 per million. They are further classed as (1) identified or known resources; (2) undiscovered or unidentified resources in areas of known thorium occurrences, where the geologic setting permits extrapolation to greater depth; and (3) possible undiscovered and unidentified resources in areas not now known to contain thorium deposits. The existence of some undiscovered deposits may be reasonably surmised, for geologic environments generally similar to those of known occurrences are present, but the location of such deposits is unknown.

TABLE 3.—*Estimated United States ThO_2 resources, in tons*

Type of deposit	Approximate cost category	Grade (ppm)	Known or identified (indicated and inferred)	Potential resources in known areas	Total	Speculative estimate of additional potential resources in districts that are undiscovered or unidentified
Vein	Low cost ($3–$10 per lb).	>3,000	100,000	[1] 400,000	[1] 500,000	([2]).
	High cost	300–3,000	20,000	[1] 500,000	[1] 500,000	([2]).
Placer	Low to moderately high cost, dependent on byproducts in part.	>15	70,000	230,000	300,000	Not estimated.
	High cost (low grade).	<15	10,000	Large, not estimated.	Large, not estimated.	Large, not estimated.
Igneous and metamorphic rock.	do	300–3,000	15,000	[3] 20,000	[3] 35,000	([4]).
	do	30–300	40,000,000	[3] 35,000,000	[3] 75,000,000	Very large, not estimated.
Sedimentary rock	do	300–3,000	20,000	[3] 60,000	[3] 80,000	([2]).
	do	30–300	55,000	[3] 300,000	[3] 350,000	Large, not estimated.

[1] Extrapolated to 3,000-ft depth.
[2] Probably at least as great as potential resources in previous columns.
[3] Extrapolated to 1,000-ft depth.
[4] Probably several times the total in preceding column.

Identified or known resources include those in districts or areas for which some quantitative information is available. Only a small amount of the resources in this category can be classed as measured ore, but indicated and inferred ore are included. Resources are generally estimated to a depth of 1,000 feet for large bodies of igneous rock, or to a depth equal to half the surface length for smaller deposits such as veins. The sizes of placer deposits in the known-resources category are fairly well established by physical exploration.

In the undiscovered or unidentified resources category, veins are estimated to a depth of 3,000 feet. Resources in igneous and sedimentary rocks are estimated to a depth of 1,000 feet, although in most districts included in these estimates, geologic conditions would permit extrapolation of the low-grade resources to at least 3,000 feet. Estimates shown for the igneous and sedimentary rocks could therefore be trebled with reasonable likelihood that the tonnages of thorium present at those depths will be comparable, on the average, to those at the surface. The estimates for placer deposits, on the other hand, cannot be projected to great depth, although additional placer deposits will no doubt be found in some now untested areas. Potential resources inferred to occur in the epigenetic deposits at depths of several hundred feet or more will require costly exploration for their discovery and evaluation. Very little subsurface exploration of thorium veins has been carried out thus far.

There is no satisfactory basis on which to make meaningful estimates of possible undiscovered and unidentified resources, particularly of veins and other epigenetic deposits, in areas not known to contain thorium deposits and in large areas in which unfavorable sedimentary or volcanic rock types obscure more favorable host rocks at depth. Accordingly these estimates are, for the most part, expressed qualitatively in the tables. Potential resources undoubtedly exist in this category, and present a challenge to exploration in the future.

Concentrations of 3,000 ppm or more are found almost exclusively in vein-type deposits, and veins containing this much thorium were of commercial interest at prices prevailing in the 1950–60 period. Recorded thorite production (U.S. Bureau of Mines, 1957-59) from veins in the Western States was chiefly in the 1957–59 period but has probably aggregated less than 1,000 tons. A large part of this was in 1958, when production of 650 tons of upgraded thorite concentrate, valued at $35,000, was reported in Colorado (Kelly, 1962). Known near-surface vein deposits of a grade of about 0.5 percent would presumably be economically workable at a price of about $3 to $5 per pound ThO_2. The workability is of course determined by many factors in addition to the ThO_2 content of the material; hence the grade expressed here in parts per million is only an approximate guide to amount of ThO_2 in deposits minable at a given price.

The identified resources in veins are largely in the Lemhi Pass district, Idaho-Montana, for which the U.S. Atomic Energy Commission (1962) has estimated reserves of about 100,000 tons at 0.5 percent

ThO_2. Other districts with smaller known high-grade resources, but for which some data are available, include the Wet Mountains and Powderhorn districts, Colo.; Porthill, Idaho; Bokan Mountain, Alaska; Mountain Pass, Calif.; and Capitan Mountains, N. Mex. The known reserves are approximated from available data by projecting the better known deposits to depths equal to half their lengths. Undiscovered resources in those areas known to contain thorium deposits are estimated by extrapolating this figure to a depth of 3,000 feet, for the veins are commonly found over areas having a relief of 1,000 to 3,000 feet. The figure obtained by this method for the seven districts gives a minimum potential for veins in the United States. To this may be added other districts, which have promise as potential sources of thorium but which have not yet been adequately evaluated, such as the Bear Lodge Mountains, Wyo.; Wausau, Wis.; Chico Hills and Gallinas Mountains, N. Mex.; St. Peters Dome, Colo.; Cottonwood area, Ariz.; Salmon Bay, Alaska; Hicks Dome, Ill.; several iron deposits in New Jersey and New York; and various small showings in other areas, chiefly in the Western States.

The amount of thorium in veins in undiscovered districts is problematical. Known thorium veins are chiefly in areas of Precambrian rocks or are associated with small intrusive bodies commonly of Tertiary age. These geologic environments are extensive, and the seven districts for which some reserve data are available make up only about 800 square miles or less than one-half percent of the total area of such rocks. Much of the remaining area has been prospected by radiometric methods, and negative results tend to diminish the potential, but new discoveries will probably be made by more thorough exploration. It is conjectured that new discoveries and further exploration of other occurrences already known but inadequately evaluated could increase by a factor of 2 or more the resources of thorium in veins.

Placer deposits are of considerable economic interest at 30 ppm ThO_2, which is approximately equivalent to 2 lbs monazite per cubic yard as mined commercially in Idaho from 1950 to 1955. Even 15 ppm, roughly the ThO_2 content of 1 lb monazite per cubic yard, or less, is potentially minable by low-cost dredging methods. Placer deposits represented in the known or identified resources in table 3 are those in the Piedmont, Coastal Plain, and beaches of the Southeastern United States, and in the Idaho batholith area. Undiscovered potential resources of placer deposits include potential areas not yet evaluated in these same regions, together with a small potential estimated for other placers that may be found in the Western States, including Alaska.

An estimate of the monazite content of the middle shoal off the mouth of Appalachicola River, Fla. (Tanner and others, 1961), indicates a possible 5×10^5 cubic meters of monazite, or about 137,500 short tons ThO_2, in this one shoal. As this shoal has not been fully tested by subsurface exploration, it has been included in table 3 in potential resources in known areas, at a grade exceeding 15 ppm ThO_2. If similar quantities of monazite occur in other shoals along the coast of the Southeastern States, the total resources in this type of deposit may be large.

Other thorium-bearing surficial materials, which have been included in the estimates for placers, are residual deposits such as bauxite. The undiscovered resources in known districts in the 30–300 ppm range include 8,400 tons ThO_2 for Arkansas bauxite, based on an average of 93 ppm ThO_2 for two samples (Adams and Weaver, 1958; Gordon and others, 1959).

Low-grade resources that would presumably be submarginal, or only in part marginal, at a price of $10 per pound of ThO_2, are included in table 3. Some of this material may become workable through improved technology or higher prices. Very large tonnages of submarginal resources can be found at the low grades represented by table 3 in igneous, sedimentary, and metamorphic rocks and in placer deposits. The estimates shown in the table are in part qualitative, and they are but a small part of what might be listed if more quantitative data were available on these low-grade materials.

Veins containing less than 3,000 ppm ThO_2, which would be marginal at a price of $10 per pound of ThO_2, may become of economic interest if demand for thorium increases sufficiently. These veins are chiefly in the Wet Mountains, Lemhi Pass, and Powderhorn districts. They have been estimated to a 3,000-foot depth, by assuming that in known districts such veins are as plentiful at that depth as they are at the surface.

Exploration of placer deposits provides some basis for a least minimum estimates for the Idaho batholith placers containing less than 15 ppm ThO_2, but present information does not justify an estimate, although it could be large, for such low-grade placers that may be present but undiscovered in other regions.

The estimates in table 3 of low-grade resources in igneous and metamorphic rocks include about 300 square miles each of Conway Granite, New Hampshire, and Elberton Granite, Georgia; small bodies of igneous rock in the Wet Mountains, Front Range, and Powderhorn districts, Colorado; small parts of the Silver Plume and Boulder Creek Granites, Colorado; the Mountain Pass and Rock Corral areas in southern California; and metamorphic rock zones at Southbridge, Mass., all of which contain thorium in the range of 30–300-ppm ThO_2. The small tonnage tabulated as known in rock exceeding 300-ppm ThO_2 represents a pegmatitic facies of the albite syenite stock in the Wet Mountains, Colo., and a zone in metamorphic rock near Worcester, Mass. Other small bodies of similar rock probably exist, however. The tonnages in igneous and metamorphic rock have, for consistency, been calculated to a uniform depth of 1,000 feet, although there is little question that most could reasonably be extrapolated to greater depth. Igneous rocks with less than 30 ppm (less than 3 times the average crustal abundance of thorium) are plentiful but are not included as resources because of low grade. The amount of thorium in areas other than those listed would no doubt vastly increase the resources in igneous and metamorphic rocks in the 30–300-ppm ThO_2 range if more quantitative data were available.

Resources in sedimentary rocks shown in table 3 are based largely on information about the Goodrich Quartzite in northern Michigan (Vickers, 1956a), the Cretaceous black-sand deposits in the Rocky Mountain region (Dow and Batty, 1961), and the conglomerate of the Deadwood Formation at Bald Mountain in northern Wyoming (Borrowman and Rosenbaum, 1962). The Cretaceous and Tertiary sediments of the southeastern Coastal Plain contain, in the aggregate, very large tonnages of thorium in low concentrations (Dryden, 1958), although little is known about the average grade of material in bodies of minable size.

The Chattanooga Shale, like most shales, contains about 10 ppm ThO_2, but the uranium content is 6 times as great. The Gassaway Member of the Chattanooga Shale contains 7 to 9 ppm thorium, and in the area of about 5,000 square miles in which uranium reserves were estimated it contains about 1,100,000 tons of thorium (Andrew Brown, written commun., 1962). If the shale were mined for uranium and other valuable constituents in low concentration, some thorium might be recoverable as a byproduct, but, because of its low concentration, this thorium has not been included in table 3.

Other possible resources of thorium in sedimentary rocks are suggested by the large uranium and thorium reserves in conglomerate and quartzite in the Blind River district in southern Ontario. Inasmuch as the Blind River district contains the largest uranium and thorium reserves in North America, similar conglomerate or quartzite beds elsewhere must be assigned a considerable potential. However, deposits of this type, other than the Goodrich Quartzite deposits near Palmer, Mich., have not been discovered in this country, despite extensive radiometric prospecting.

WORLD

Current estimates of known high-grade thorium reserves of the world, totaling about 740,000 tons, are shown in table 4. These estimates are compared to the approximate areas of Precambrian rocks and other metamorphic and igneous rocks as an indication of relative thorium potential that is more realistic than would be obtained by comparing total land areas. Precambrian and other metamorphic and igneous rocks in the United States comprise roughly 2.8 percent of exposed areas of such rocks in the world. Because the United States is one of the more thoroughly prospected countries, this ratio, applied to the reserves and potential resources estimated for the United States, may give some idea of the potential of less thoroughly prospected parts of the world.

TABLE 4.—*Known world thorium reserves in relation to areas of Precambrian and other high-grade metamorphic and igneous rocks*

P, placer deposits; R, concentrations in igneous and metamorphic rocks; S, concentrations in sedimentary rocks; V, veins.

Country	Thorium reserves (short tons)			Principal types of deposits	References
	High-grade deposits (figures rounded)		Per sq mi of Precambrian and other high-grade metamorphic and igneous rocks		
North America	300,000		0.1		
United States		100,000	.3	V, P	U.S. Atomic Energy Commission (1962).
Canada		200,000	.1	S, R	Griffith (1963).
Other		Small	Small		
South America	30,000		.02		
Brazil		[1] 30,000	.02	P, R	U.S. Atomic Energy Commission (1959).
Other		Small	Small		
Asia	[2] 250,000		.2		
India-Ceylon-Nepal-Pakistan-Afghanistan.		[2] 250,000	.5	P	Do.
China		Small	Small		
Other		Small	Small		
Africa	50,000		.01		McKinney (1960).
Malagasy Republic		10,000	.07	P, R	Roubault (1956).
West Africa		15,000	.02	R, P	Bowie (1959).
Nyasaland		10,000	.1	P	Do.
South Africa		10,000	.06	V	Pike (1958).
Egypt		10,000	.25	P	Higazy and Naguib (1958).
Other		Small	Small		
Europe and U.S.S.R.	100,000		.08		
U.S.S.R. and eastern Europe		100,000	.1	R, P	McKinney (1960).
Other		Small	Small		
Australia	10,000		.02	P, V	Parker (1962).
World total	[2] 740,000		0.06		

[1] Figure includes known and assumed additional reserves. In addition to the figures shown for Brazil, 130,000 tons of thorium in the low-grade (0.07 percent ThO_2) carbonatite at Araxa might be recoverable as a coproduct of columbium mining (Guimaraes, 1957).
[2] An additional 250,000 tons is possible in the inland placers of Bihar and West Bengal, which have not been thoroughly explored.

Although thorium occurrences in the United States are not typical of those known in other parts of the world, this extrapolation leads to a figure of 3,600,000 tons for potential resources for the world in high-grade deposits comparable to those mined under economic conditions of the 1950–60 period. This figure is probably underestimated, for it is based on known reserves only and takes no account of undiscovered deposits at depth and in districts yet to be found. Furthermore, at least one of the geologic factors controlling the concentration of thorium—chemical weathering to release heavy minerals for concentration in placer deposits—has not operated in the United States to nearly the degree that it has in the tropical regions of the world.

If India, rather than the United States, were used for comparison, the resulting world total would be 6 to 12 million tons (table 4, footnote 23). This figure is not really tenable, however, because in India a particularly fortuitous combination of geologic conditions has effected the concentration of thorium in deposits. Table 4 brings out the favorability of Africa for discovery of additional reserves, because the tonnage (0.01) per square mile for known reserves is small for an area that otherwise seems geologically favorable for thorium deposits.

McKelvey (1960) used a method to estimate the extent of undiscovered resources based on the fact that the reserves of many elements in the conterminous United States that have been sought and mined for a long time are roughly equal to their abundance (A) in the earth's crust in percent times a billion or ten billion. Known world reserves of elements long sought and mined are also closely related to their crustal abundance, and are roughly equal to $A \times 10^9$ to $10^{10} \times 17.3$ (17.3 is the factor used to extrapolate United States reserves to the world in proportion to area of land surface). This relation provides a means of estimating the reserves of lesser known elements that we might expect to be developed when exploration for them has reached a stage comparable to that for elements long sought and mined.

The estimates made by this method tend to undervalue the total potential because the total resources, even of elements long sought and mined, must be much greater than reserves known at the present stage of exploration, and this low figure is the only one available for extrapolating reserves of the lesser known elements; furthermore, estimates made by this method make no allowance for low-grade resources that may be minable some time in the future. Accordingly, the estimates made by this method yield minimum figures probably well below the tonnages that may be found by thorough future exploration.

McKelvey's method of crustal abundances indicates that the world reserves of thorium, in potentially minable concentrations greater than about 0.05 percent in hard-rock deposits and in easily mined placer deposits, should be on the order of 10 to 20 million tons when exploration for thorium reaches a stage as advanced as that for other elements.

The estimates in table 4 are for known high-grade reserves only, and are considerably less than the expectable total potential resources of similar material based on the relation between crustal abundance and the reserves of other elements. This disparity may result in part from the fact that because thorium is not as soluble in hydrothermal solutions as uranium and some other metals, more of it is dispersed in common rocks. The scarcity of high-grade concentrations found thus far is somewhat compensated by the fact that thorium minerals occur widely in placer deposits, from which small concentrations can be recovered cheaply. Of the known reserves shown in table 4, roughly one-half is in placer deposits. Thorium-bearing veins of the type found since 1950 in the United States and South Africa may, however, be discovered in other parts of the world. The numbers and sizes of veins present at depths of 1,000 to 3,000 feet may be assumed to be similar to those at the surface. Thus the various estimates presented in tables 3 and 4 may be extrapolated to yield an estimate of potential world resources that is of the same order of magnitude as that based on average crustal abundance of thorium. The discovery and development of much of these undiscovered resources will require very costly exploration and expensive mining; thus these resources must be considered largely high cost potential resources until economic conditions, technical advancement, and increased geologic and exploratory efforts make their discovery possible.

Resources of thorium in low-grade submarginal materials are very inadequately known. Shown in figure 2 are some estimates of tonnages in a few deposits, but data are inadequate to extrapolate from these to total potential United States or world resources. Enough examples are known, however, to show that low-grade resources of thorium are very large.

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