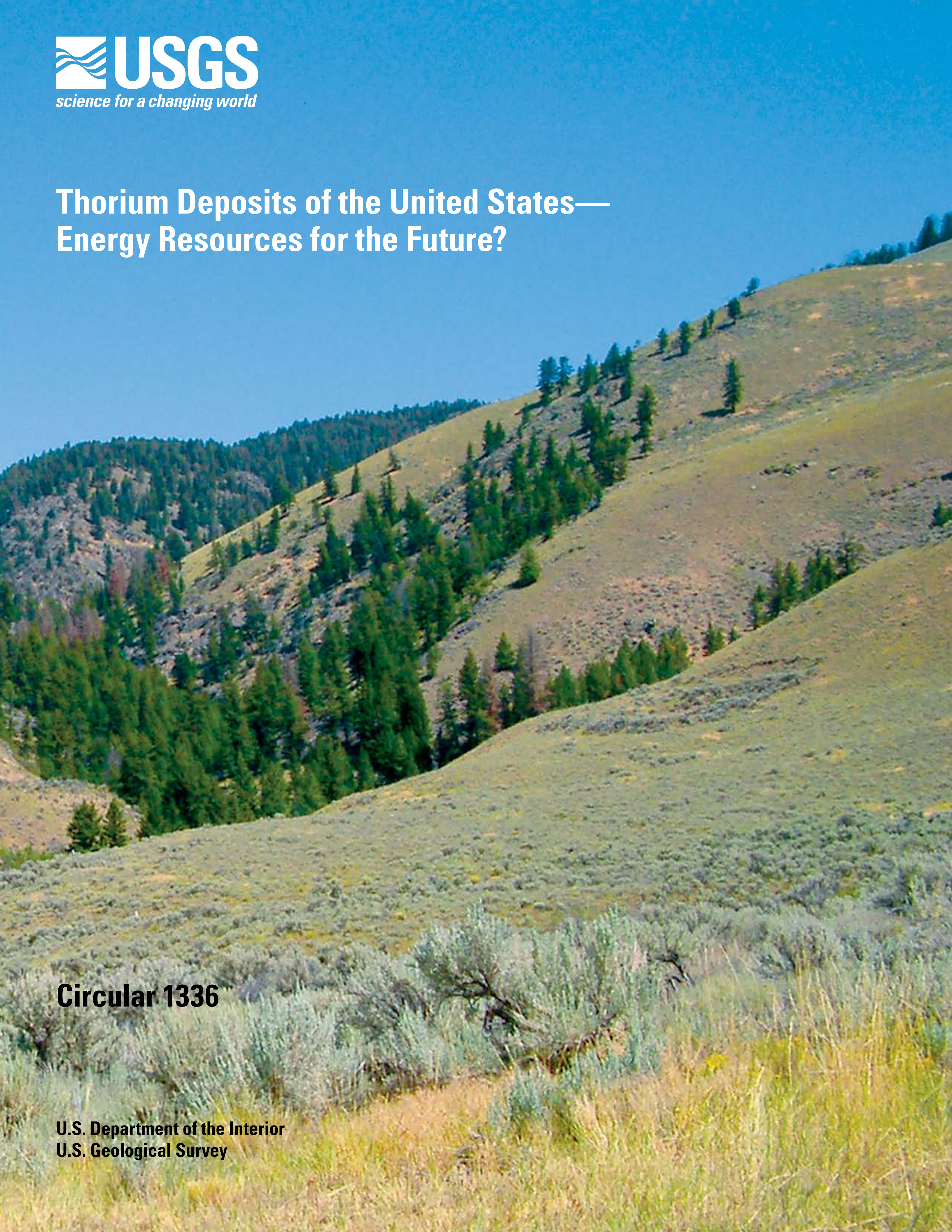

Thorium Deposits of the United States— Energy Resources for the Future?

Circular 1336

U.S. Department of the Interior
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Cover photograph. View to the north of the Lucky Horseshoe prospect (middle left of photograph), which is one group of numerous exploration trenches, cuts, and short adits that explored thorium-rich vein systems of the Lemhi Pass thorium district in the 1950s to 1980s. More than 200 thorium-rich veins in the Beaverhead Mountains form the Lemhi Pass district, Idaho and Montana. This district is thought to contain the largest concentration of thorium resources in the United States and is the site of renewed thorium exploration activity.

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KEN SALAZAR, Secretary

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Conversion Factors

Multiply	By	To obtain
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
square kilometer (km^2)	0.3861	square mile (mi^2)
metric ton (t)	1.1023	ton, short (2,000 lbs.)

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Introduction

Many nations are exploring new ways to meet their growing energy supply needs, with a particular focus upon methods that produce lower carbon dioxide emissions compared to traditional oil, natural gas, and coal power plants. As a result, thorium-based nuclear power has experienced renewed attention as a potential energy source (Branan, 2008).

India, in particular, has committed much research towards the development of thorium-based nuclear energy. An internet search of the terms "India" and "thorium" reveals considerable information on India's recent efforts to bring a thorium-based reactor online in the near future. One of the main reasons for India's interest in thorium-based nuclear energy (an interest they have pursued for several decades) is that although the country has relatively small uranium deposits, it does possess large indigenous thorium deposits. Easily exploitable thorium deposits include large accumulations of monazite in alluvial deposits along India's southern coasts (Bhola and others, 1958; Mahadevan and others, 1958).

The potential use of thorium as a nuclear energy source was studied as early as 1946 at the Oak Ridge National Laboratory in Tennessee (Weinberg, 1994). However, in contrast to uranium, widespread use of thorium-based energy has yet to be realized. Several test reactors designed in the United States, Europe, Japan, Russia, and India have successfully generated electricity using thorium fuel sources. Although successful, these technologies have not advanced beyond experimental reactors thus far. The world supply of uranium has been inexpensive and adequate to meet supply needs, so there has been less incentive for a new nuclear energy technology to replace or complement uranium-based reactors.

Thorium has several apparent advantages over uranium as a power source: (1) thorium is about three times more abundant in the Earth's crust than uranium; (2) many thorium deposits contain other mineral resources of value, such as rare earth elements; (3) the spent-fuel waste products of thorium fission are not the types used in nuclear weaponry (such as plutonium, a byproduct of uranium power generation); and (4) the thorium-based spent fuels contain fewer radioactive elements and are smaller in volume and mass than conventional uranium-based nuclear wastes.

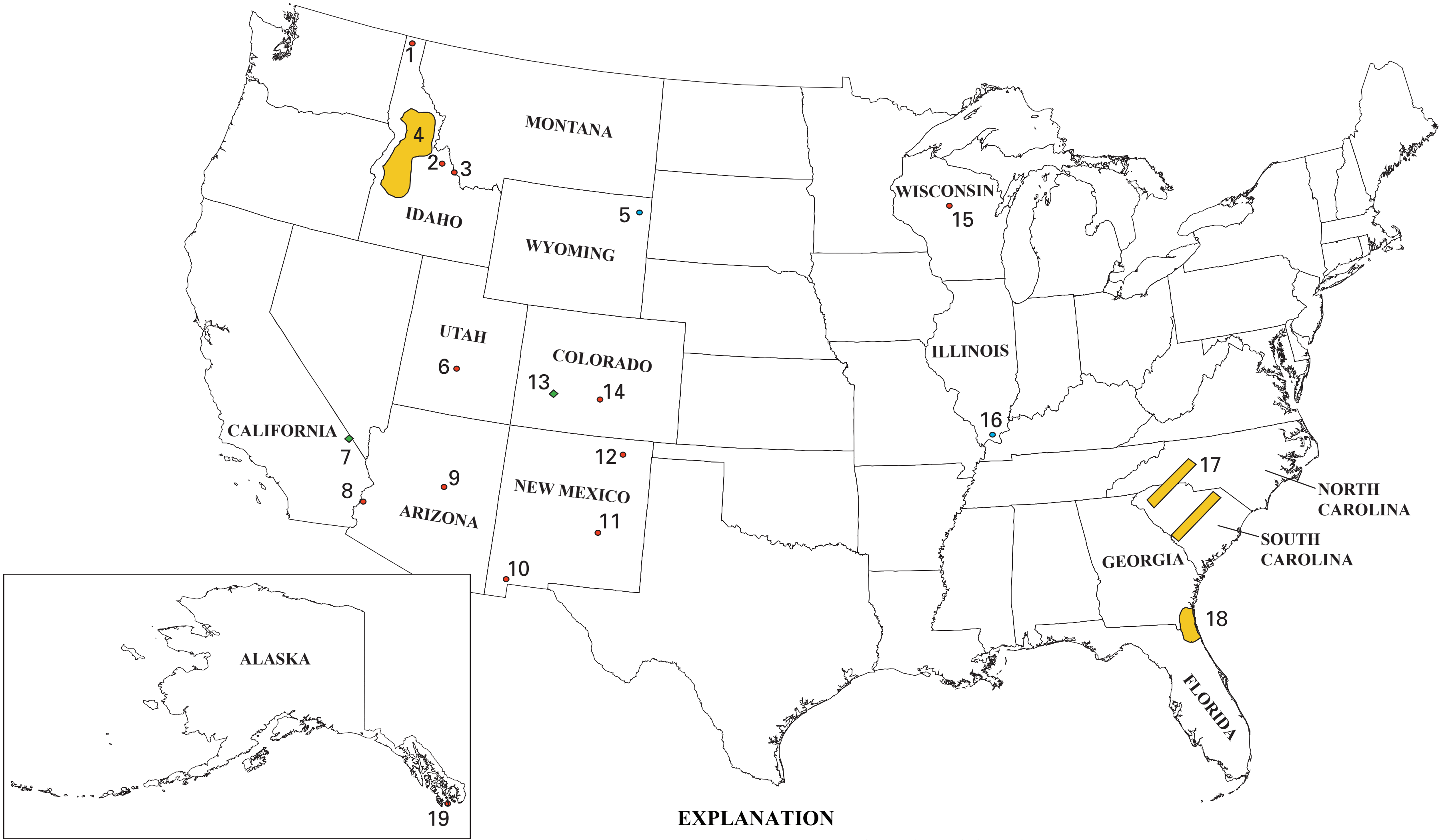
If India or another country can prove successful in generating electricity safely and efficiently from a thorium-based nuclear power plant, then considerable interest and activity will focus on thorium exploration across the globe. Recently, the U.S. Congress has expressed interest in thorium-based energy (Branan, 2008). Thus, it benefits the United States and other countries to identify and evaluate their indigenous thorium resources. This report describes the geology and resources of the principal thorium districts of the United States (fig. 1).

Thorium Deposits of the United States

Thorium minerals occur in alkaline igneous rocks and carbonatites, but the most concentrated deposits occur in epigenetic veins that surround alkaline igneous complexes. Thorium's genetic association with alkaline igneous rocks also places thorium in close association with minerals that host other valuable elements, such as those containing rare earth elements (REE), titanium, niobium, and phosphorus. Large titanium deposits can exist in the ultramafic units of the alkaline igneous complex (Van Gosen and Lowers, 2007). In addition to metallic resources, many of the rock units of these alkaline complexes, such as nepheline syenite and carbonatite (an apatite source), can have industrial mineral uses in their raw crushed form. Several alkaline intrusions contain deposits of vermiculite, formed by the surficial weathering and alteration of mica minerals (biotite, phlogopite). Alluvial concentrations of thorium minerals (mainly monazite; table 1) occur with other heavy minerals of industrial value, such as ilmenite, rutile, magnetite, zircon, garnet, staurolite, tourmaline, kyanite, and sillimanite.

Table 1. Ideal compositions of the thorium minerals described in this report.

Mineral	Ideal composition or range of composition
Monazite	$(Ce,La,Y,Th)PO_4$
Thorite	$(Th,U)SiO_4$
Brockite	$(Ca,Th,Ce)(PO4)\cdot H_2O$
Xenotime	$(Y,Th)PO_4$
Euxenite	$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$



EXPLANATION

● **Vein districts**

1. Hall Mountain, Idaho
2. Diamond Creek area, Idaho
3. Lemhi Pass district, Idaho-Montana
5. Bear Lodge Mountains, Wyoming
6. Monroe Canyon, Utah
7. Mountain Pass district, California
8. Quartzite district, Arizona
9. Cottonwood area, Arizona
10. Gold Hill district, New Mexico
11. Capitan Mountains, New Mexico
12. Laughlin Peak, New Mexico
13. Iron Hill, Colorado
14. Wet Mountains area, Colorado
15. Near Wausau, Wisconsin
19. Bokan Mountain, Alaska

Disseminated deposits

● **Alkaline intrusions**

5. Bear Lodge Mountains, Wyoming
16. Hicks Dome, Illinois

◆ **Carbonatite stocks**

7. Mountain Pass carbonatite, California
13. Iron Hill carbonatite, Colorado

▨ **Black sand placer deposits**

4. Idaho placers
17. North and South Carolina placers
18. Florida-Georgia beach placers

Figure 1. Index map of thorium districts in United States.

The significant thorium deposits in the United States occur in:

- Epigenetic veins peripheral to alkaline intrusions,
- Alkaline igneous complexes or carbonatites, and
- Alluvial stream and beach deposits (placers) derived from the erosion of alkaline igneous terranes.

Carbonatite.—A rare, carbonate igneous rock formed by magmatic or metasomatic processes. Most carbonatites consist of 50 percent or more primary carbonate minerals, such as calcite, dolomite, and (or) ankerite. They are genetically associated with, and therefore typically occur near, alkaline igneous rocks. Thorough treatises on carbonatites are provided by Tuttle and Gittins (1966), Heinrich (1980), and Bell (1989).

Alkaline igneous rocks.—A series of igneous rocks that formed from magmas and fluids so enriched in alkali elements that sodium- and potassium-bearing minerals form constituents of the rock in much greater proportion than "normal" igneous rocks. Alkaline igneous rocks—sometimes referred to as "alkalic rocks"—are characterized by feldspathoid minerals and (or) alkali pyroxenes and amphiboles. For detailed discussions about alkaline igneous rocks and their scattered geographic distribution, refer to Sorensen (1974) and Woolley (1987).

Epigenetic Vein Deposits

Thorium vein districts contain the largest tonnage high-grade thorium resources in the United States. Two thorium-vein districts in particular host the majority of the known high-grade thorium resources in the United States—the Lemhi Pass district along the border between southwestern Montana and Idaho, and the Wet Mountains area of south-central Colorado (fig. 1).

Lemhi Pass Thorium District, Montana-Idaho

The Lemhi Pass district contains numerous thorium-rich veins within a 140 km^2 core of a larger 400 km^2 area in the central Beaverhead Mountains; the district straddles the Continental Divide on the Montana-Idaho border (fig. 2). This district is thought to represent the largest concentration of thorium resources in the United States (table 2). Earlier studies by the U.S. Geological Survey (USGS) estimated that the Lemhi Pass district contains total reserves of 64,000 metric tons (t) of thorium oxide (ThO_2) and probable potential resources of an additional 121,000 t (Staatz and others, 1979). The 10 largest veins, with an average grade of 0.43 percent ThO_2, represent 95 percent of the district's identified thorium resources. Using a compilation of surface, underground, and drilling assays, the Idaho Energy Resource Company reported a "quantitative proven" reserve of 176 t of ThO_2 within the Last Chance vein with a possible resource of 2,000 t of additional ThO_2 (Idaho Energy Resource Company, written commun., 2008). The Last Chance vein and the Wonder vein (fig. 3) are the only deposits in the district that have been sampled by underground or drill hole access. Much exploration potential exists in the district.

Table 2. Estimated reserves of ThO_2 in the significant thorium districts of the United States.

[Estimates from Armbrustmacher (1988) for the Wet Mountains area, Colorado, and from Staatz and others (1979, 1980) for the other deposits]

District	Total ThO_2 reserves, metric tons (t)
Vein deposits	
Lemhi Pass district, Montana-Idaho	64,000
Wet Mountains area, Colorado	58,200
Hall Mountain, Idaho	4,150
Iron Hill, Colorado	1,700 ("thorium veins") 690 (carbonatite dikes)
Massive carbonatites	
Iron Hill, Colorado	28,200
Mountain Pass, California	8,850
Placer deposits	
North and South Carolina stream placers	4,800
Idaho stream placers	9,130
Florida beach placers	14,700

Figure 2. View to west of Lemhi Pass. The ridge, a part of Beaverhead Mountains, forms a segment of the Continental Divide and the Idaho-Montana border, with Montana in foreground and Idaho in distance. More than 200 thorium-rich veins in this area form the Lemhi Pass district, thought to represent the largest concentration of thorium resources in the United States.

Within the Lemhi Pass district, Staatz (1972a, 1979) mapped 219 veins enriched in thorium and REE. Most of these veins are quartz-hematite-thorite veins, which fill fractures, shears, and brecciated zones in Mesoproterozoic quartzite and siltite host rocks (fig. 3). Thorium also occurs in monazite-thorite-apatite shears and replacements with specularite, biotite, and alkali feldspar. The thorium veins of the district range from 1 m to at least 1,325 m in length and from a few centimeters to as much as 12 m in width. The Last Chance vein (1,325 m long and 3–8 m wide over most of its length) is the longest and widest vein in the district; this vein also represents the largest individual thorium resource in the district. Fifteen thorium veins in the district exceed 300 m in length. Some of the veins contain carbonate minerals, such as calcite, siderite, and ankerite, and local fluorite. Rare-earth- and thorium-bearing allanite and monazite are locally abundant. Other reported ore minerals include brockite, xenotime, and thorite. The primary gangue minerals include quartz, hematite, limonite, apatite, potassium feldspar, biotite, albite, and barite. Most of the veins are extensively weathered and have abundant iron-oxide staining. The district also hosts small quartz-copper-gold-veins (and rare molybdenum), and some of the thorium veins contain sparse amounts of base metals, such as copper, iron, manganese, lead, and zinc.

The thorite veins of the Lemhi Pass district are approximately equally enriched in thorium and REE: the ratio of thorium to REE concentrations in the veins averages around 1:1. Staatz (1972a) reported the REE analyses of 31 vein samples, which showed total REE-oxide contents ranging from 0.073 to 2.20 percent, with an average value of 0.428 percent (very similar to the average thorium oxide content of 0.43 percent found in the 10 largest veins in the district). The thorium veins are most often enriched in the middle REE (especially neodymium), with some veins apparently enriched more in the heavy REE (Staatz, 1972a, p. 76–77). Using modern techniques, recent analytical work by the Idaho

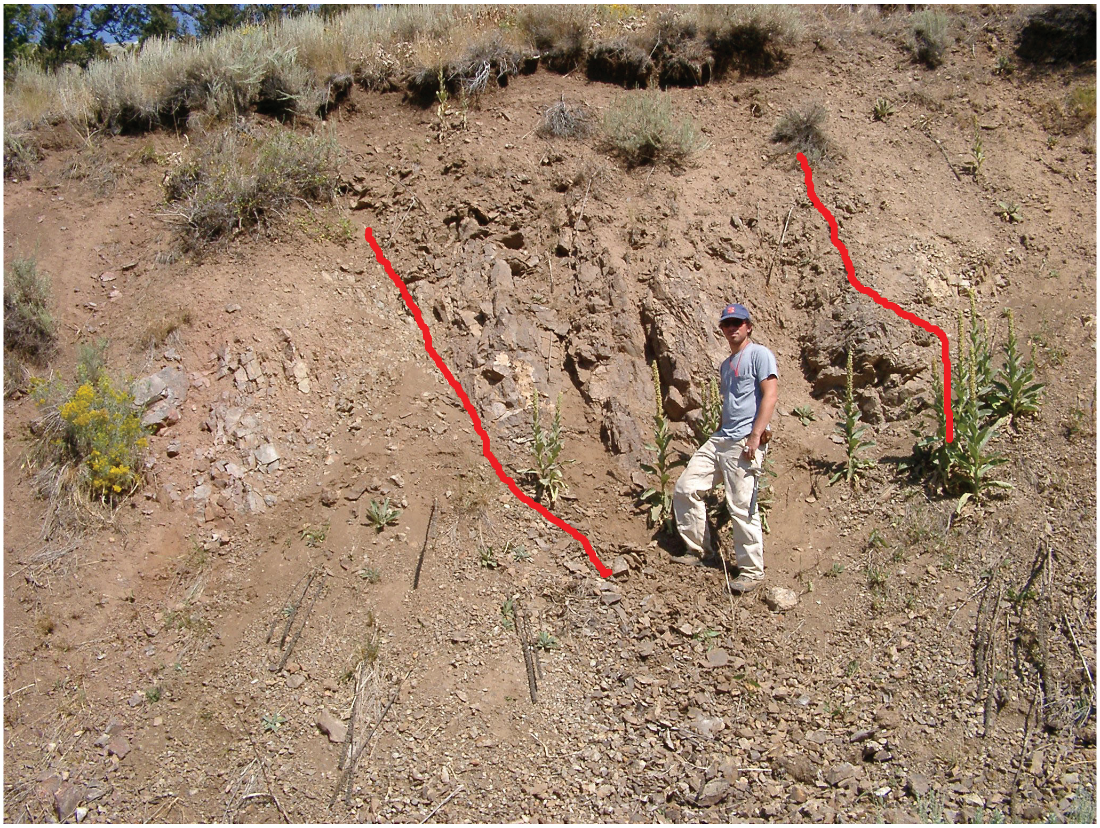


Figure 3. Outcrop of Wonder vein (between red lines), Lemhi Pass district, exposed in a mined bench. Vein is heavily oxidized and consists mainly of silica, likely some carbonate, and iron oxide minerals with thorite and altered thorite. Host rock is Precambrian quartzite and siltite.

Geological Survey and industry (Thorium Energy in 2008; Idaho Energy Resource Company in 1991) has confirmed the overall thorium and REE levels along with the unusual middle REE-group enrichment in the veins.

In many places the type of high-grade, thorium-REE vein system found in the Lemhi Pass district can be clearly linked to nearby alkaline magmatic features; however, no obvious features of alkaline magmatism were noted in the earlier geologic descriptions of the area. Thorium-bearing quartz veins can occur as far as several kilometers from the center of an alkaline intrusive system. Yet, no alkaline igneous body was known within tens of kilometers of the Lemhi Pass area, and the age of the mineralization was unknown, but thought to be Tertiary. However, recent mapping by the Idaho Geological Survey, supplemented by geochronology, has discovered copper or thorium-REE veins that are cut by structures likely Cretaceous in age, as well as thorium veins that terminate against pre-Tertiary unconformities. The recent field studies also discovered a small outcrop of Cambrian (529 Ma U-Pb age on zircon) syenite (80 percent feldspar) that is cut by nonradioactive specular hematite veins in the central part of the district (Gillerman and others, 2008). In addition, $^{40}Ar/^{39}Ar$ geochronology on hornblende in mafic dikes, including lamprophyres, indicates Paleozoic or older igneous ages, and alteration-related feldspars and biotite in the thorium deposits have ages that appear to be older than Jurassic. Some evidence for the possible presence of an underlying carbonatite is provided by (1) the carbonate minerals present in many of the district's veins, (2) one breccia pipe with a calcite matrix adjacent to a mafic dike, and (3) a few carbonate-bearing mafic dikes in the area. Identification of the syenite and numerous alkaline mafic rocks, coupled with carbonate alteration, provides a potential association between the quartz-hematite-thorite-REE veins of the Lemhi Pass district and alkaline magmatism. These observations suggest that the veins of the Lemhi Pass region could represent distal parts of a buried alkaline intrusive complex, which was later structurally disrupted by regional Cretaceous thrusting and Tertiary extensional faulting (Gillerman and others, 2003; Gillerman and others, 2008). Altered, thorium-enriched intrusives are known farther south in the Beaverhead Mountains (Staatz and others, 1972), but their exact genetic and age relations to the Lemhi Pass veins are unknown. Veins in the Diamond Creek area, Lemhi County, Idaho, are very similar to those at Lemhi Pass and are most likely related. Many geologic questions about the Lemhi Pass area have yet to be answered.

Wet Mountains Area, Colorado

This thorium district, which is located in Fremont and Custer Counties of south-central Colorado, may be comparable in thorium resources to the Lemhi Pass district of Idaho-Montana (table 2). The thorium deposits occur over an area of about 60 km north-to-south by 24 km west-to-east. Thorium occurs in veins, syenite dikes, fracture zones, and carbonatite dikes (Armbrustmacher, 1988) associated with three Cambrian-age alkaline complexes (Olson and others, 1977) that intruded the surrounding Precambrian terrane. These alkaline complexes are (1) the McClure Mountain Complex (Shawe and Parker, 1967; Armbrustmacher, 1984), (2) the Gem Park Complex (Parker and Sharp, 1970), and (3) the complex at Democrat Creek (Armbrustmacher, 1984). The thorium-mineralized veins and fracture zones, which are distal to the three alkaline intrusive complexes, have the highest economic potential for thorium resources. The USGS estimated that the vein and fracture zone deposits of the Wet Mountains area contain reserves of 58,200 t of ThO_2 and probable potential resources of 145,600 t of ThO_2; the seven largest carbonatite dikes in the district contain additional reserves of 119 t of ThO_2 and probable potential resources of 683 t of ThO_2 (Armbrustmacher, 1988).

The thorium veins and fracture zones are linear features, typically 1–2 m thick, but a few are as much as 15 m thick (fig. 4). Some individual thorium veins can be traced in outcrop for 1,500 m and some radioactive fracture zones as much as 13 km. Most of these vein- and fracture-zone deposits occur within a 57 km^2 tract of Precambrian gneiss and migmatite located south and southeast of the quartz syenite complex at Democrat Creek. Christman and others (1953, 1959) mapped nearly 400 veins in this area. The major minerals forming these veins are smoky and clear quartz, microcline, barite, iron oxides, carbonates, and accessory rutile and sulfide minerals. Waxy, red thorite is the primary thorium mineral. When broken, the veins and surrounding fenite emit a strong fetid odor produced by a variety of hydrocarbon and sulfur-bearing compounds (Armbrustmacher, 1988), which Heinrich and Anderson (1965) attributed to hydrocarbon-fluorine gas of magmatic origin. The odor-producing component in the thorite veins “may be the fugitive constituents of complexing agents that combined with thorium to produce a highly mobile species capable of being transported under pressure-temperature conditions that existed in the hydrothermal solutions” (Armbrustmacher, 1988, p. F5–F6). The veins, fracture zones, joints, and associated faults of the area trend mainly northwest-southeast and cut across the foliation of the host Precambrian metamorphic rocks at nearly right angles. On the basis of the analysis of 201 samples of veins and fractures, Armbrustmacher (1988) found an average grade of 0.46 percent ThO_2, with an average thorium:total-REE ratio of about 2.2:1.

Thorium mineralization in the Wet Mountains district also took place in carbonatite dikes and small plugs. The carbonatite dikes are especially associated with the McClure Mountain complex (Staatz and Conklin, 1966). The carbonatites occur in a variety of forms, such as (1) composite dikes with two or more generations of carbonate side-by-side with lamprophyre (Heinrich and Salotti, 1975; Armbrustmacher and others, 1979); (2) phreatic explosion breccia pipes satellite to the McClure Mountain complex (the Pinon Peak breccia pipes of Heinrich and Dahlem, 1967); and (3) siliceous carbonate dikes associated with amethyst veining (the Amethyst carbonatites of Heinrich and Shappirio, 1966). Armbrustmacher (1979) separated the carbonatites into two groups: (1) replacement carbonatites and (2) primary magmatic carbonatites. Replacement carbonatites have microscopic textures that indicate the nearly complete pseudomorphous replacement of the relict igneous dike mineralogy by carbonate minerals. The replacement carbonatite dikes have ThO_2 contents of <0.1 percent (Armbrustmacher and Brownfield, 1978). In contrast, the primary magmatic carbonatite dikes do not display mineral replacement textures and are enriched in elements and minerals typical of magmatic carbonatites, including enrichments in thorium, niobium, and REE residing in the minerals thorite, bastnasite, synchysite, ancylite, and monazite. Thorium concentrations in the primary magmatic carbonatite dikes often exceed 0.1 percent ThO_2. Armbrustmacher and Brownfield (1978) reported an average value of 0.17 percent ThO_2, with a high value of 2.0 percent ThO_2. However, thorium is more concentrated and occurs in more volume in the quartz-iron oxide-barite vein- and fracture-zone deposits of the district in comparison to the carbonatites (Armbrustmacher, 1988).

The Wet Mountains area also contains thin (≤2 m thick) red syenite dikes that contain anomalous thorium and REE, particularly where the dikes are located nearest the intrusive centers. The syenite dikes are composed primarily of alkali feldspar and ferric oxides, with trace amounts of thorite, barite, rutile, xenotime, bastnasite, and brockite (Armbrustmacher, 1988). Samples of red syenite veins analyzed by this study found only 30–40 ppm (parts per million) Th, equivalent to 0.0034–0.0046 percent ThO_2.

Sampling and geochemical analyses conducted during this study found that the syenite, mafic, and ultramafic rock units that form the core of the three intrusive complexes do not contain significant concentrations of thorium. Samples of the quartz syenite pluton of the complex at Democrat Creek had an average content of 62 ppm Th (0.007 percent ThO_2). Gabbro and pyroxenite units of the Gem Park complex showed no greater than 13 ppm Th. In the McClure Mountain complex, all samples of the plutonic units of hornblende-biotite syenite (fig. 5), nepheline syenite, pyroxenite, and gabbro had <10 ppm Th.

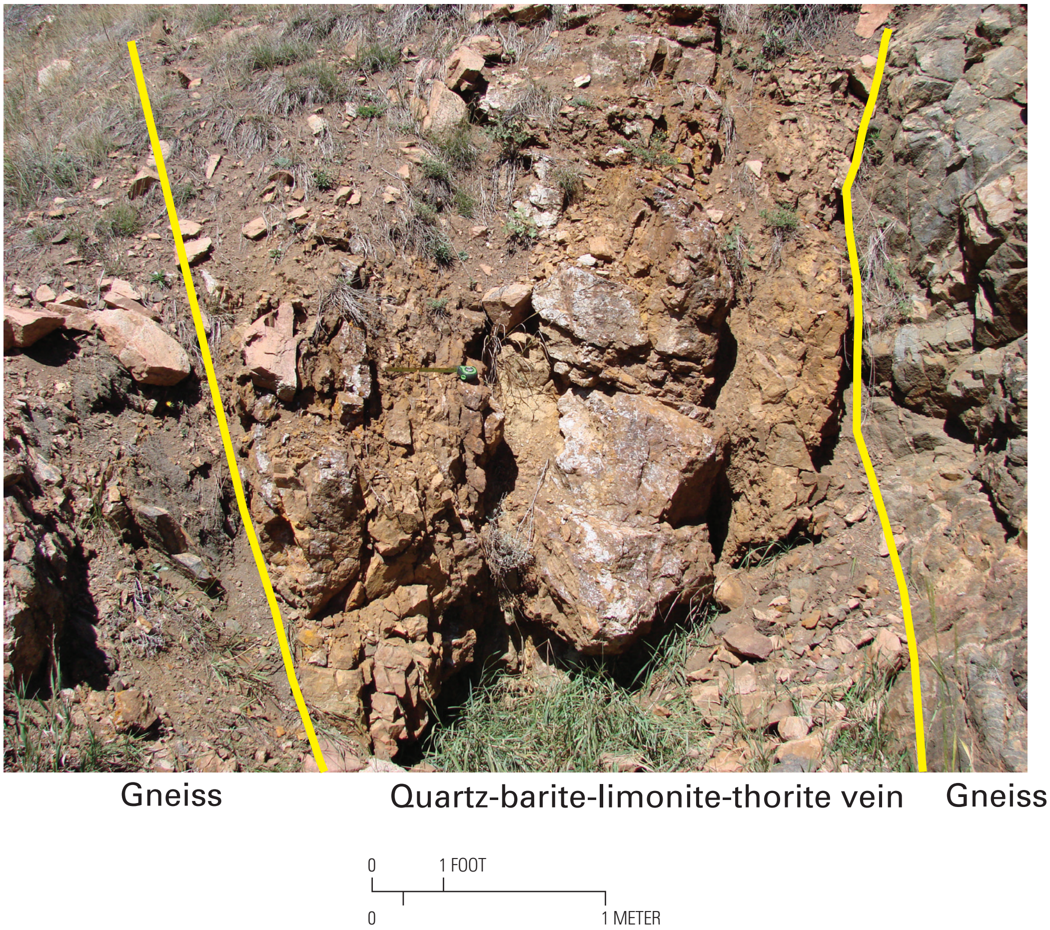


Figure 4. Sewell Ranch thorium vein (between yellow lines), Wet Mountains area, Custer County, south-central Colorado. This northwest-southeast-trending Cambrian thorium-rich vein, 9 ft (2.7 m) wide here, cuts about perpendicular to foliation of Precambrian mafic gneiss country rock. Channel sampling of this vein by Christman and others (1953, p. 26–27) found as much as 0.60 percent equivalent ThO_2.

Other Thorium Vein Districts in the United States

Several other areas with thorium veins exist in the United States (Staatz, 1974; Staatz and Armbrustmacher, 1982), but they all appear to contain significantly less thorium reserves than the Lemhi Pass district of Idaho-Montana and the Wet Mountains area of Colorado. Other districts that contain thorium veins (fig. 1) include:

- Alaska: Bokan Mountain district, southern part of Prince of Wales Island (MacKevett, 1963; Staatz, 1978; Staatz and others, 1980, p. 19–22; Thompson, 1988)
- Arizona: Cottonwood area, Yavapai County; Quartzite district, Yuma County (Staatz, 1974)
- California: Mountain Pass district, San Bernardino County (Olson and others, 1954; Castor and Nason, 2004)
- Colorado: Iron Hill carbonatite complex (Powderhorn district), Gunnison County (Hedlund and Olson, 1961; Temple and Grogan, 1965; Olson and Wallace, 1956; Olson and Hedlund, 1981)
- Idaho: Hall Mountain, Boundary County (Staatz, 1972b); Diamond Creek area, Lemhi County (Anderson, 1958; Staatz, 1974)
- New Mexico: Capitan Mountains, Lincoln County; Gold Hill district, Grant County; Laughlin Peak, Colfax County; and other minor deposits (McLemore and others, 1988)
- Utah: Monroe Canyon, Sevier County (Staatz, 1974)
- Wisconsin: near Wausau, Marathon County (Vickers, 1956)
- Wyoming: Bear Lodge Mountains, Crook County (Staatz, 1983)

Figure 5. View to west of McClure Mountain, Fremont County, Colo., composed of hornblende-biotite syenite phase of McClure Mountain complex. This stock is genetically related to thorium deposits of Wet Mountains area. However, this rock unit, and other core units of three intrusive complexes in this area, contain only modest thorium concentrations of <100 parts per million. The thorium resources occur in epigenetic vein and fracture-zone deposits (fig. 4) distal to the alkaline intrusive complexes.

Of these vein deposits, perhaps the most noteworthy are those of Hall Mountain, located just south of the Canadian border near the middle of the Idaho panhandle. Although these thorium-rich veins are exposed across an area of only about 1,830 m by 300 m, they may be the highest grade thorium veins known in the United States. Select vein material from this district (Staatz, 1972b) contained as much as 24 percent ThO_2 content. The primary vein minerals are quartz and calcite, and the principal thorium-bearing mineral is thorite. Staatz (1972b) described the mineralogy of the Hall Mountain veins and contrasted them to those of the Lemhi Pass district. The veins of Hall Mountain intruded Middle Proterozoic quartzite and quartz diorite sills (Purcell Lava) of the lower part of the Prichard Formation of the Belt Supergroup. The veins range in length from 2 to 270 m and in thickness from thin seams to 4 m (Staatz, 1972b). The larger veins of the district average about 4.0 percent ThO_2, but they are few in number. Thus, Staatz and others (1979) estimated that the veins of the Hall Mountain district contain total reserves of about 4,150 t of ThO_2 (table 2).

Environmental Considerations

In addition to the disturbance and impacts typically associated with the surface and underground mining of vein deposits, the development of thorium veins should also consider several other potential environmental aspects, including:

- The mine wastes and ore materials extracted from thorium vein deposits are radioactive materials that thereby require special handling and transportation considerations.

- These vein types can have moderately high sulfur content, but this sulfur occurs primarily in sulfate form as barite, which is quite insoluble.
- Thorium-REE veins generally contain low sulfide mineral content, and therefore have little ability to generate acidic waters.
- The carbonatite veins and masses have an inherent capacity for acid neutralization due to their high carbonate content.
- The thorium-ore minerals are resistant to chemical breakdown, forming relatively insoluble detrital minerals. Thus, thorium minerals contribute only trace concentrations of thorium (about 1 part per billion) to natural waters (pH 5–9). Thorium is very insoluble in most natural waters.

A detailed discussion of the potential environmental aspects of thorium-REE vein deposits is provided by Armbrustmacher and others (1995).

Disseminated Low-Grade Thorium Deposits

Large-volume, low-grade deposits of thorium occur in carbonatite stocks and some alkaline intrusions in the United States. Carbonatites are commonly enriched in thorium and REE (Deans, 1966; Heinrich, 1980; Mariano, 1989). That the thorium in the majority of these intrusions would be developed as the primary commodity seems unlikely; however, thorium could be recovered as a byproduct along with the extraction of associated mineral resources. Examples of large-tonnage thorium-bearing carbonatites and alkaline intrusions in the United States are described in the following.

Carbonatite Stocks

The carbonatite stock at the center of the Iron Hill (Powderhorn) carbonatite complex in southwestern Colorado (figs. 1, 6) is the largest exposed carbonatite mass in the United States, cropping out over an area of about 3.7 km long by 1.9–0.8 km wide (Olson, 1974; Hedlund and Olson, 1975; Olson and Hedlund, 1981). The carbonatite stock is the youngest unit of this classic carbonatite-alkaline rock intrusive complex, emplaced about 570 million years ago (Olson and others, 1977; Olson and Hedlund, 1981) in an area about 35 km south-southwest of Gunnison in Gunnison County, Colo. The primary rock units of the complex include (from oldest to youngest): pyroxenite, uncompahgrite, ijolite, nepheline syenite, and the carbonatite (Temple and Grogan, 1965; Nash, 1972; Olson, 1974; Hedlund and Olson, 1975; Olson and Hedlund, 1981; Armbrustmacher, 1983).

Much of the complex of Iron Hill has significant mineral resource potential owing to enrichments in titanium, REE, thorium, niobium (columbium), vanadium, and deposits of vermiculite and nepheline syenite (Van Gosen and Lowers, 2007). The pyroxenite unit of the complex hosts the largest known titanium reserve in the United States (Thompson, 1987; Shaver and Lunceford, 1998; Van Gosen and Lowers, 2007). The carbonatite stock is enriched in REE, thorium, and niobium. The anomalous thorium is mainly due to concentrations of the thorium-rich mineral thorite, and at least partially due to monazite and pyrochlore (the niobium host mineral), which each contain lower thorium content than thorite. Staatz and others (1979) estimated that the carbonatite stock of Iron Hill consists of 655.6 million t of carbonatite, averaging 0.0043 percent ThO_2 (38 ppm Th), thereby representing a potential resource of 28,200 t of ThO_2 (table 2). Sampling of the Iron Hill carbonatite stock by Armbrustmacher (1980) found an average content of 0.0041 percent ThO_2 (36 ppm Th). Sampling of the carbonatite stock conducted for this study (13 samples; Van Gosen, 2008) found the following *median* values: 1,630 ppm total REE (0.20 percent REE oxide), including 680 ppm Ce; 31 ppm Th (0.0035 percent ThO_2); and 416 ppm Nb (0.06 percent Nb_2O_5).

The highest thorium concentrations in the Iron Hill complex occur in discontinuous veins (“thorium veins”) and mineralized shear zones composed of quartz-plagioclase-calcite-iron oxide-thorite that cut the Precambrian granite and metamorphic rocks that surround the complex. The thorium veins and shear zone deposits range in width from a few centimeters to 5.5 m (mostly less than 0.3 m), and they range in length from a meter to the 1,067-m Little Johnnie vein, which occupies a mineralized fault (Olson and Wallace, 1956; Hedlund and Olson, 1961). These vein and shear zone deposits are estimated to contain reserves of about 1,700 t of ThO_2 (Staatz and others, 1979). In addition, several hundred carbonatite dikes have been identified within 1.6 km of the complex, radiating outward from the carbonatite stock and cutting all of the earlier formed intrusive rocks of the complex and the Precambrian rocks bounding the complex. These dikes are usually 1–2 m wide, but one dike is about 46 m wide. The dikes are discontinuous, but can typically be traced for about 90–150 m along strike. Staatz and others (1979) estimated that the 13 longest carbonatite dikes hold reserves of about 690 t of ThO_2 (table 2).

Another prominent, thorium- and REE-bearing carbonatite mass in the United States is the Mountain Pass deposit near the east edge of the Mojave Desert in the northeast corner of San Bernardino County, Calif. This carbonatite deposit has world-class REE reserves of more than 18 million t of ore with an average grade of 8.9 percent rare earth oxide (Castor and Nason, 2004). The typical ore contains about 10–15 percent bastnasite (the ore mineral), 65 percent calcite and (or) dolomite, and 20–25 percent barite, plus other minor accessory minerals (Castor and Nason, 2004). The massive carbonatite core is called the Sulphide Queen body, which has an overall length of 730 m and average width of 120 m (Olson

Figure 6. View to northwest of Iron Hill, Gunnison County, southwestern Colorado. Iron Hill is formed by a massive carbonatite stock, which forms the center of an alkaline intrusive complex. This complex hosts multiple mineral resources, including titanium, niobium, rare-earth elements (REE), and thorium (Van Gosen and Lowers, 2007). The carbonatite stock of Iron Hill is estimated to consist of 655.6 million metric tons (t) of carbonatite containing 2.6 million t of REE oxides, 28,200 t of ThO_2, and 373,700 t of Nb_2O_5 (Staatz and others, 1979, p. 30).

and others, 1954). Projecting the Sulphide Queen body down dip for 152 m (500 ft), Staatz and others (1979) suggested that this mass comprises about 33.4 million t of carbonatite containing approximately 8,850 t of ThO_2 (table 2). However, mining to date (2009) has not recovered the thorium and, furthermore, the thorium here has been considered an environmentally deleterious element because of its radioactivity.

Alkaline Intrusions

Many alkaline intrusions in the United States contain average ThO_2 concentrations of several tens of ppm, but few exceed 100 ppm. As examples, the alkaline Conway Granite of New Hampshire (Adams and others, 1962) and alkaline granite of the Darby pluton of the Seward Peninsula, Alaska (Miller and Bunker, 1976), have similar average ThO_2 contents of approximately 65 ppm. Although plutons of such large volume represent very large thorium resources, thorium deposits of this low grade seem unlikely as primary targets for development. Two disseminated thorium deposits of large volume and somewhat higher grade—Hicks Dome in southern Illinois and the Bear Lodge Mountains deposit of northeastern Wyoming (fig. 1)—are summarized in the following.

Hicks Dome lies in Hardin County of southernmost Illinois. The dome-shaped structure, approximately 14.5 km in diameter, was formed by the displacement of sedimentary rocks at least 1,200 m upward above an alkaline intrusion at depth. More than 600 m of sedimentary rocks, mostly limestone, were pushed up by the explosive intrusion of magmatic fluids (Heyl and others, 1965). A hole drilled near the apex of the dome (Brown and others, 1954) intercepted a mineralized breccia at a depth of 490 m (1,607 ft) and remained in breccia to the bottom of the hole at 897 m (2,944 ft). Analysis of eight samples of this drill core, each 7.6–9.1 m (25–30 ft) long, had thorium concentrations ranging from 0.007 to 0.18 percent ThO_2 (Brown and others, 1954). These samples represent only 64 m (210 ft) of a thorium-enriched breccia zone that could extend across the roof of Hicks Dome over a large area. Shallow diamond drilling and trenching sampled another area of radioactive breccia atop Hicks Dome, in which the radioactive mineral was tentatively identified as monazite, found in association with florencite, a cerium-aluminum phosphate (Trace, 1960). Using airborne gamma-ray data, Pitkin (1974) delineated the extent of the thorium anomaly at Hicks Dome. However, the considerable depth to this thorium deposit limits its resource potential. Much more surface and subsurface exploration is necessary to evaluate the extent and grade of this thorium deposit.

A disseminated thorium deposit lies in the southern Bear Lodge Mountains, about 8 km northwest of Sundance, Crook County, Wyo. The deposit is hosted by alkaline intrusions of middle Tertiary age, primarily trachyte and phonolite; they intruded Paleozoic and Mesozoic sedimentary rocks, forming a dome about 13 km long by 10 km wide. The alkaline igneous rock crops out in an oval pattern over an area of 9 km long by 4 km wide (Staatz and others, 1979). The igneous core is microfractured and altered. Thorium mineralization in the thin fractures formed coatings and veinlets as much as 6 mm thick. The coatings and veinlets consist predominantly of iron and manganese oxide minerals, along with feldspar and quartz. The thorium occurs in monazite, thorite, and brockite. Thorium concentrations vary across the alkaline intrusive core, ranging from 46 ppm ThO_2 in apparently unmineralized rock to 1,200 ppm (0.12 percent) in rock crisscrossed by many veinlets (Staatz and others, 1979). On the basis of 52 samples collected within an area of 2.4 by 1.6 km, where the alkaline rock has numerous small veinlets, Staatz and others (1979, p. 27) delineated three subareas: "(1) The northern area has an average grade of 0.023 percent ThO_2 and 0.75 percent combined rare-earth oxides, (2) the central area has an average grade of 0.042 percent ThO_2 and 1.71 percent combined rare-earth oxides, and (3) the southern area has an average grade of 0.035 percent ThO_2 and 1.35 percent combined rare-earth oxides." They also noted that drilling "indicates that the veining extends at least 1,200 ft [365 m] below the surface."

Black Sand Placer Thorium Deposits

Globally and in the United States, alluvial accumulations of monazite are a significant type of thorium deposit. For example, the alluvial monazite deposits of the Coastal Belt of southernmost India are thought to represent one of the largest thorium resources in the world. The monazite deposits of southern India contain detrital heavy minerals and are found in piedmont lakes, in shallow seas, in parts of the beaches (fig. 7), in sand bars across the mouth of rivers, in deltas, and in sand dunes behind the beaches (Bhola and others, 1958). A study by Mahadevan and others (1958) estimated that the beach sands of the southwestern coast of India alone contain estimated reserves of 446,400 t (492,200 short tons) of monazite, in which the ThO_2 content of the monazite varies from 7.5 to 9 percent.

Monazite is a REE- and thorium-bearing phosphate mineral [$(Ce,La,Y,Th)PO_4$] whose thorium content can range from a few percent to 20 percent. Monazite's resistance to chemical weathering and high specific gravity accounts for its association with other resistant heavy minerals such as ilmenite, magnetite, rutile, and zircon. Monazite weathers from alkaline crystalline rocks of the surrounding region and is transported downstream and deposited by alluvial processes.

In the United States, alluvial deposits of monazite are known to occur in the intermontane valleys of Idaho, the Carolina Piedmont of North and South Carolina, and the beach deposits of northeastern Florida–southeastern Georgia. In the past, mining of these unconsolidated stream deposits was conducted by small-scale sluicing (Idaho and North and South Carolina) and dredges (Idaho); beach sands were mined by large shovels (Florida-Georgia). Sluicing instantly produces a heavy-mineral separate, but even in the case of the dredge and shovel operations, the heavy-mineral separation was still performed at the site. Thus, the mining of thorium from alluvial deposits has the advantages of relative ease of mining and rapid mineral separation, in comparison to hard-rock mining for thorium. Another benefit of placer thorium deposits is the potential for coproduct development. Coproducts can include REE obtained from monazite; titanium from ilmenite and rutile; iron from magnetite; zirconium and hafnium from zircon; and industrial-grade garnet, staurolite, tourmaline, kyanite, and sillimanite, which are used as abrasives and as refractory minerals.

As with any mining operation planned for a riparian environment, considerations beyond grade (thorium concentration) and reserves must be addressed, such as (1) assessing environmental issues associated with "in-stream mining;" and (2) obtaining access, mineral rights, and permits to work the stream channel and disturb adjacent lands as needed. Much information is available online regarding the many issues to be considered by in-stream mining operations.

The three monazite placer districts highlighted in the following—North and South Carolina stream deposits, Idaho stream deposits, and Florida-Georgia beaches—are the largest volume known alluvial thorium deposits in the United States (fig. 1). The geology and estimated thorium resources of these districts have been well described by Staatz and others (1979, the North and South Carolina placer deposits, p. 33–39) and Staatz and others (1980, the Idaho stream placers, p. 9-18, and the Florida beach deposits, p. 3–9); numerous references cited therein provide more detailed information on these deposits. Thus, we will only summarize the findings of these earlier studies.

Placer Deposits of North and South Carolina

In 1887, a few short tons of monazite were produced from stream deposits in the Piedmont region of North and South Carolina, giving this region the distinction of being the

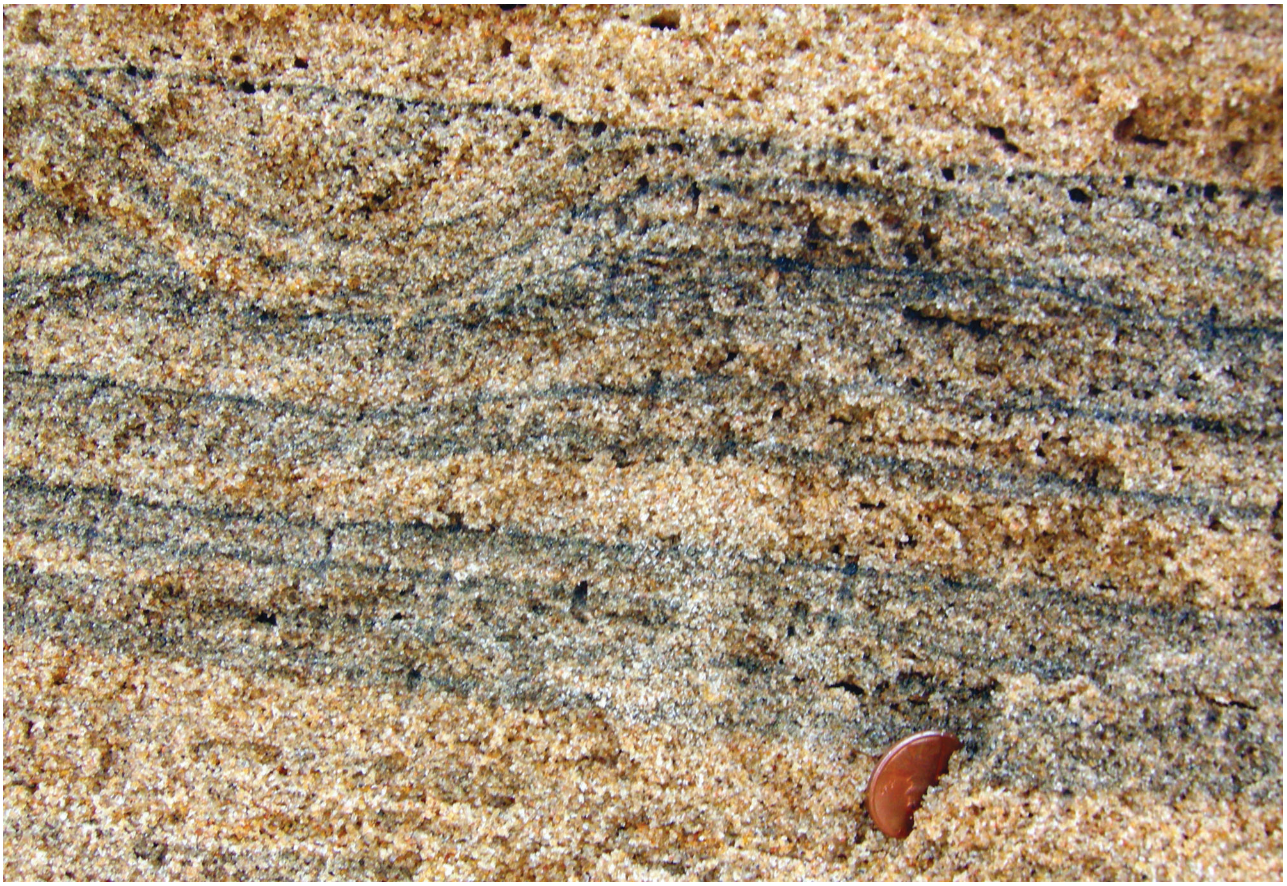


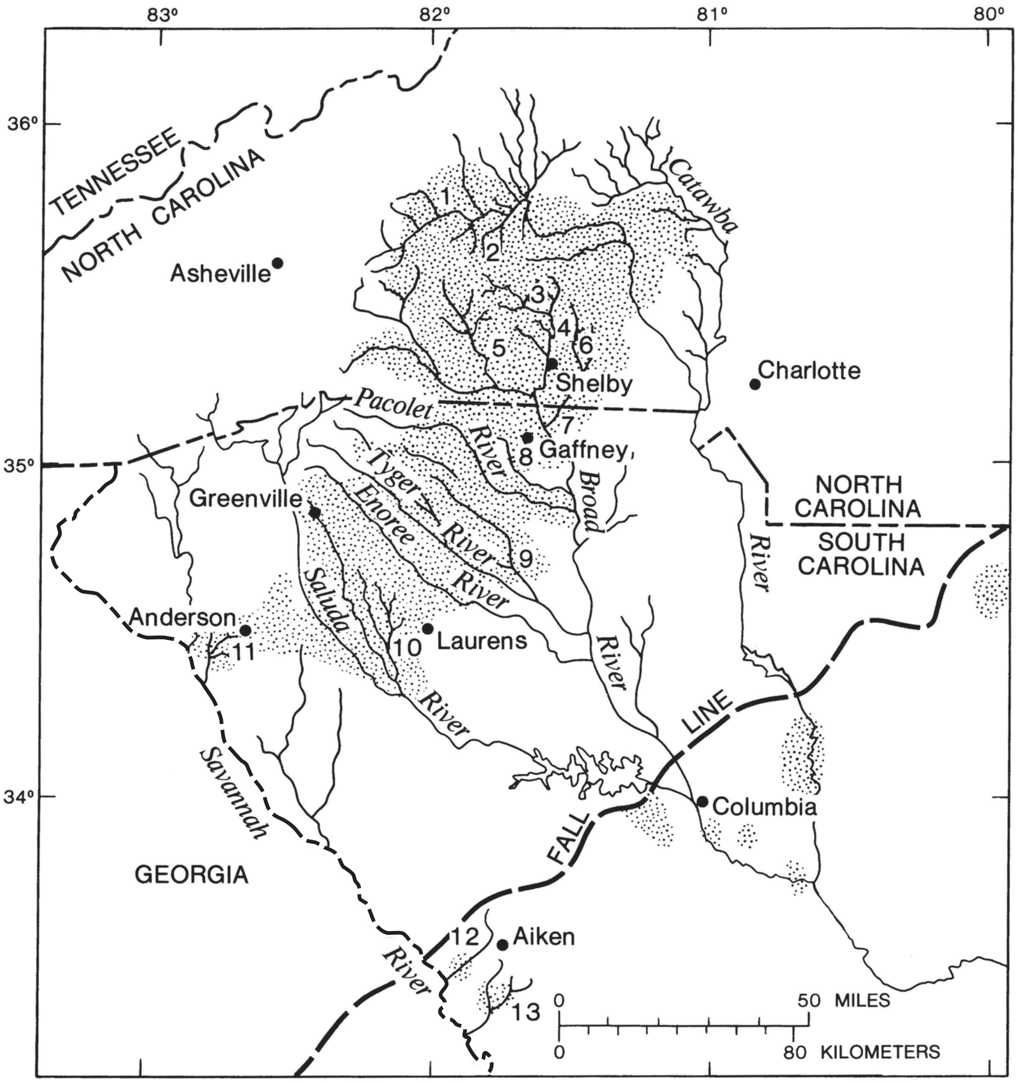
Figure 7. Heavy-mineral layers (“black sand”) in a quartz beach sand, Chennai, India. Photograph taken by Mark A. Wilson, Department of Geology, The College of Wooster, Wooster, Ohio; Mr. Wilson has granted permission for use of this photograph. Penny for scale.

world’s first supplier of thorium (Olson and Overstreet, 1964). Monazite-bearing placers of this region were worked by small-scale sluice operations from 1887 to 1911 and 1915 to 1917, producing a total of 4,973 t (5,483 short tons) of monazite (Overstreet and others, 1968). Monazite mining ended here in 1917, not because reserves had been exhausted, but rather because the beach deposits of India and Brazil were producing thorium at lower cost.

The high-grade monazite placers of the Piedmont of North Carolina and South Carolina occur between the Catawba River on the east and the Savannah River on the west (fig. 8). The stream sediment deposits across this region are generally consistent in character; the heavy-mineral concentrations are greatest in the headwaters areas. The alluvium is deposited in flat valleys, forming well-bedded, poorly graded layers of unconsolidated sediment. Stacked layers contain gravel, sand, clay, and clayey silt, at an average total thickness of about 4.5 m (Staatz and others, 1979). Monazite typically occurs in all units, but is generally most abundant in the basal gravel layers and least abundant in the clay layers. Dredging in this area between the summers of 1955 and 1958 (Williams, 1967) found heavy-mineral contents of about 1 to 1.5 percent; monazite formed about 8 percent of this fraction (Mertie, 1975). These dredging operations recovered monazite, ilmenite, rutile, zircon, and staurolite (Williams, 1967).

The region is underlain by crystalline, high-grade metamorphic rocks intruded by quartz monzonite and pegmatite. The monzonite and pegmatite intrusions vary from monazite bearing to monazite free. Overstreet (1967) suggested that the primary source of the alluvial monazite was the high-grade metamorphic rocks, particularly sillimanite schist.

According to Staatz and others (1979), the overall heavy-mineral content of the placer deposits of this region ranges from 0.15 to 2.0 percent; monazite forming about 3.5–13



EXPLANATION

▨ General area containing placers

Placers mentioned in text

1 South Muddy Creek
2 Silver Creek
3 First Broad River and its tributaries—Hinton Creek, Duncans Creek, and Wards Creek
4 Knob Creek
5 Sandy Run Creek
6 Buffalo Creek
7 Broad River at its junction with Buffalo Creek
8 Thicketty Creek
9 North Tyger River at its junction with Middle Tyger River
10 North and South Rabon Creeks
11 Big Generostee Creek
12 Horse Creek
13 Hollow Creek

Figure 8. Generalized map of known monazite-bearing placer deposits in Piedmont region of North and South Carolina. From Staatz and others (1979).

percent of the heavy minerals. They also stated that the other parts of the heavy-mineral fraction include ilmenite, 20–70 percent; garnet, 2–50 percent; rutile, 0.3–7 percent; zircon, trace to 14 percent; and sillimanite and kyanite together, trace to 20 percent. Other heavy minerals present in some placers include epidote, magnetite, xenotime, tourmaline, sphene, staurolite, andalusite, and an unidentified black radioactive mineral (Staatz and others, 1979). Analysis of 52 samples of alluvial monazite from this region (Mertie, 1975) found that the monazite contains 60-63 percent total rare-earth oxides and 2.5–7.8 percent ThO_2 content, with a mean value of 5.67 percent ThO_2.

For the 13 largest placer deposits of the Piedmont region of North and South Carolina, Staatz and others (1979) estimated total reserves of about 4,800 t of ThO_2 (table 2), with potential resources seven times higher. Their estimate was based on regional thorium resource studies by Overstreet and others (1959) and Overstreet (1967), and the studies of individual drainage basins by several others (see Staatz and others, 1979, p. 37). Future exploration for monazite placer deposits in the mid-Atlantic region can be aided by regional stream sediment geochemistry datasets assembled by the USGS (Grosz, 1993).

Placer Deposits of Idaho

A number of monazite-bearing placer districts exist in the valleys of a region that extends north of Boise, Idaho, and along the western flank of the Idaho batholith (fig. 9). Monazite was first recognized here in 1896, as the heavy, yellow to brownish-yellow mineral that collected with other heavy minerals and gold within the sluice boxes of gold placer operations in the Boise Basin near Idaho City, Centerville, and Placerville (Lindgren, 1897). In 1909, a mill designed to capture the monazite was built by the Centerville Mining and Milling Co. Only a small amount of monazite concentrate was produced before the mill burned down in a forest fire in 1910.

In the 1950s, two areas of west-central Idaho were mined by dredges for monazite recovery—Long Valley and Bear Valley (figs. 9, 10). Beginning in September 1950, Long Valley was worked by three dredges that were earlier used to recover gold, but were converted to recover monazite. The dredges were redesigned for monazite recovery with assistance from the U.S. Bureau of Mines under the sponsorship of the U.S. Atomic Energy Commission. The history of these dredging operations is described by Argall (1954) and Staatz and others (1980, p. 9–16, and references cited therein). The heavy minerals recovered in the Long Valley district were dominated by ilmenite (84 percent of heavies), followed by monazite (8 percent), garnet (5 percent), and zircon (3 percent). During this 5-year period, Staatz and others (1980) estimated that the three dredges recovered 6,430 t (7,085 short tons) of monazite containing 269 t (297 short tons) of ThO_2. The dredging ended here in mid-1955, when the government stockpile order was fulfilled.

Thorium was also unintentionally recovered within the minerals euxenite and monazite from the Bear Valley placers (fig. 10). The Bear Valley placers were worked by first one dredge in 1955, then a second in 1956, with the intent to recover niobium and tantalum for another Federal government contract. According to Staatz and others (1980, p. 10), “from alluvium of Bear Valley, 2,049 short tons [1,858 t] of euxenite, 83.5 tons [75.7 t] of columbite, and 54,862 tons [49,760 t] of ilmenite were recovered.” No records of the monazite recovery were kept.

Most of the Idaho thorium resource data used by Staatz and others (1980) came from a 1950s program in which the U.S. Atomic Energy Commission funded the U.S. Bureau of Mines to identify new domestic monazite reserves (Storch and Holt, 1963). The USGS (Staatz and others, 1980) conducted an extensive review of the results of this program, including a review of the U.S. Bureau of Mines literature, interviews with former dredge companies, and field reconnaissance and sampling of the major thorium placer districts in Idaho. They determined that the five most important thorium districts (fig. 9) are Long Valley, Bear Valley, the Boise Basin, the Burgdorf-Warren area, and the Elk City–Newsome area. The reported ThO_2 contents of monazite in the Idaho placer deposits ranges from 2.2 to 6.24 percent. Staatz and others (1980) calculated thorium reserves for each of the five major placer districts individually; they estimated that the five districts have total reserves of about 9,130 t of ThO_2 (table 2).

The primary source of the resistant thorium-bearing minerals in the Idaho placers is thought to be the Idaho batholith, in particular the quartz monzonite and pegmatite phases of the batholith (Mackin and Schmidt, 1957). The most common heavy minerals in the alluvial deposits (in generally decreasing amounts) are ilmenite, magnetite, sphene, garnet, monazite, euxenite, zircon, and uranothorite (uranium-rich thorite). In addition to REE and thorium from monazite and euxenite, the Idaho placer deposits (and the abandoned historic dredge waste piles) contain coproducts of titanium (in ilmenite), and niobium and tantalum (from euxenite).

Florida-Georgia Beach Placers

The modern and raised Pleistocene and Pliocene beach deposits of northeastern Florida and southeastern Georgia host low-grade but persistent concentrations of thorium. Heavy minerals constitute a small part of the beach sands, and monazite forms a small part of the heavy minerals. However, due to the large tonnage of suitable beach sand deposits and the ease of mining and processing this material, these beach deposits represent a very large thorium resource. Staatz and others (1980) estimated that the beach placer deposits of this region contain total reserves of about 14,700 t of ThO_2 (table 2) and 198,000 t of rare-earth oxides, which occur in 330,000 t of monazite.

Some of the heavy-mineral operations in beach deposits of Florida were once domestic suppliers of monazite. Staatz and others (1980, p. 3) noted “During 1978 monazite was produced from two of the three operating heavy-mineral deposits in

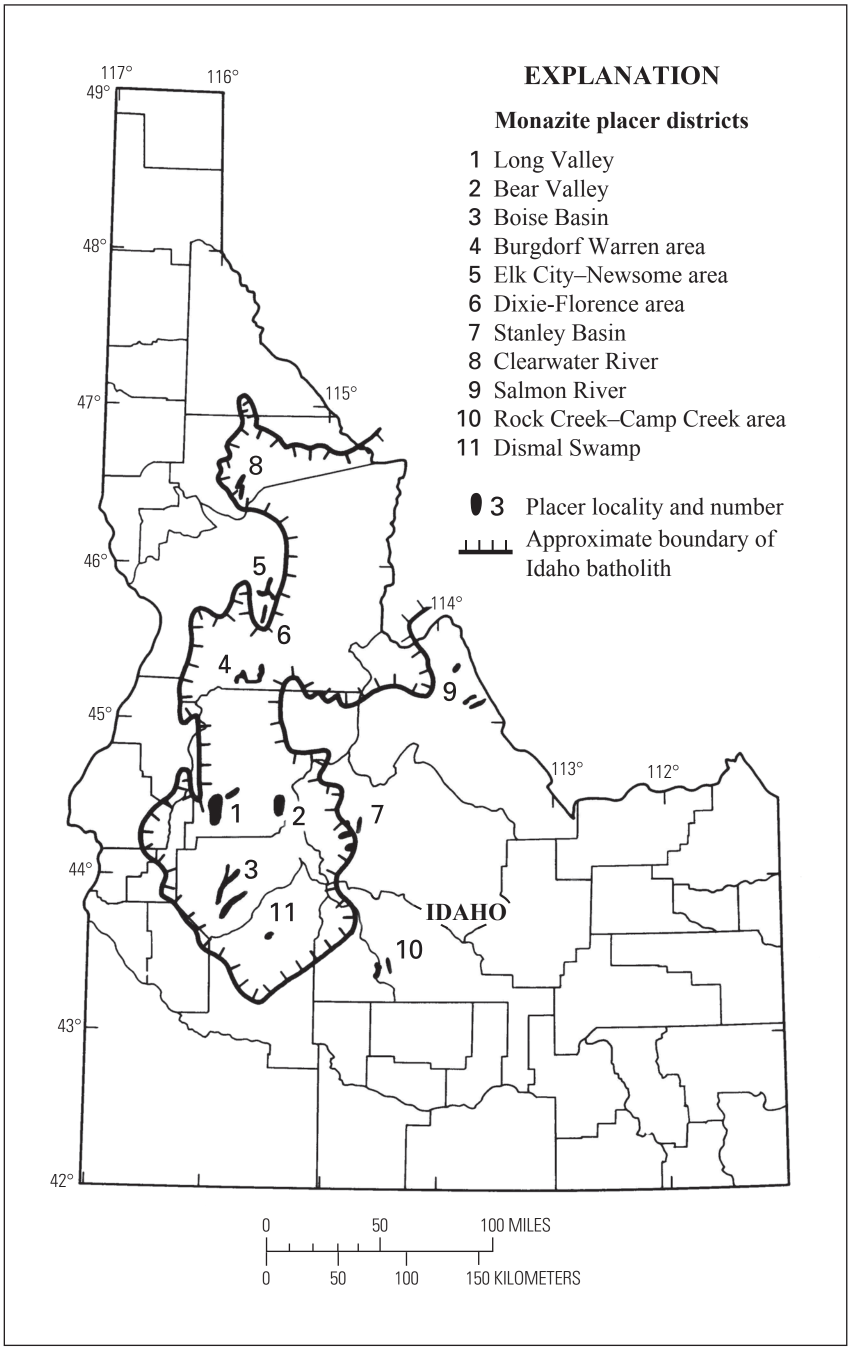


Figure 9. Generalized map of known monazite placer districts in Idaho. From Staatz and others (1980).

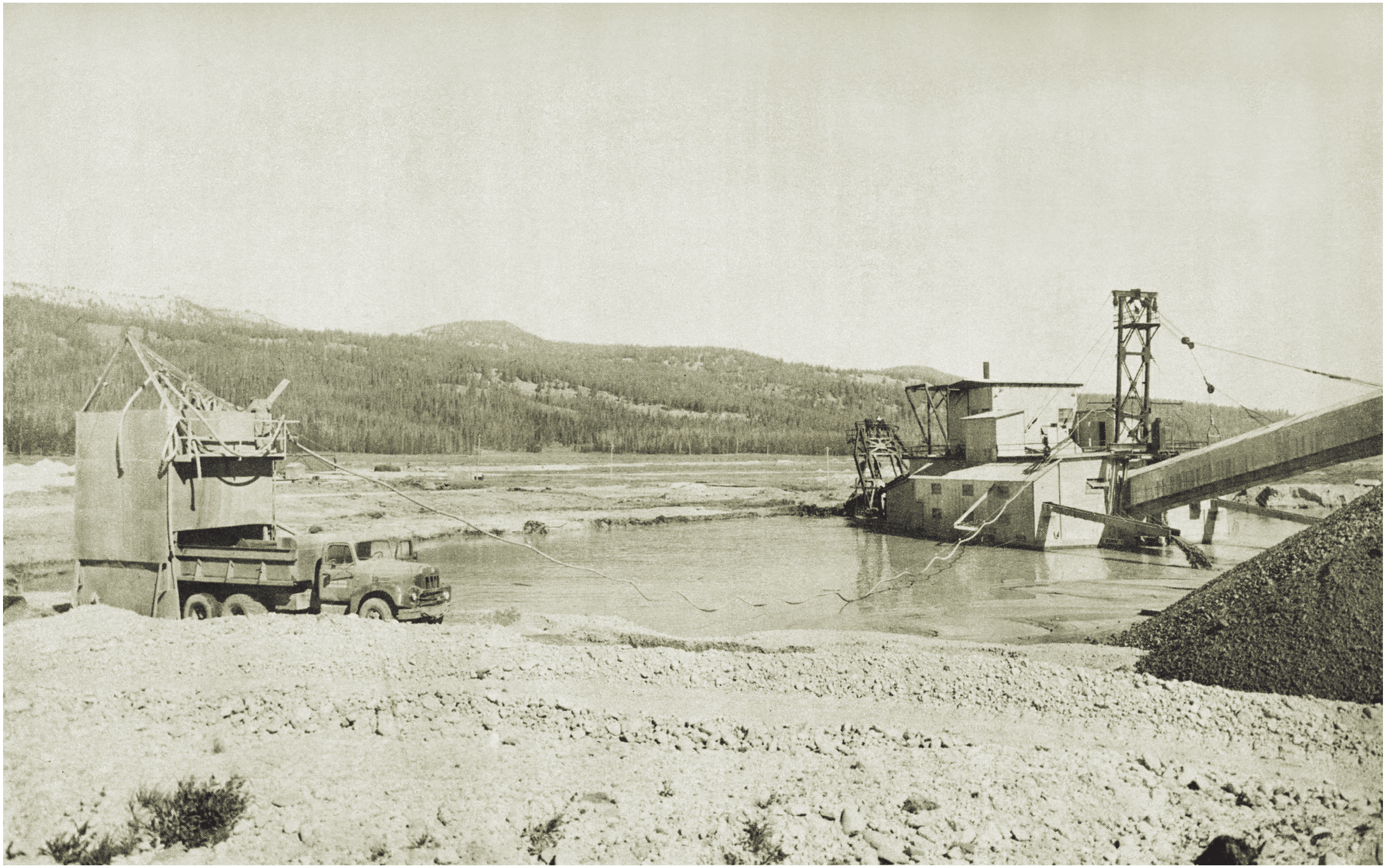


Figure 10. Porter Brothers dredge in Bear Valley (Idaho) columbium-tantalum placer deposits. This dredge operated from 1955 to 1960; exact date of photograph is unknown. Monazite was produced as a byproduct from these placer deposits. Photograph from Savage (1961, fig. 13); used with permission of Idaho Geological Survey.

Florida: Titanium Enterprises at Green Cove Springs and Humphrey Mining Corporation at Boulogne recovered monazite as a byproduct." These deposits were mined primarily for titanium (in ilmenite and rutile), which was used by the pigment industry. Other minerals sold from these deposits include kyanite, sillimanite, staurolite, garnet, and the host sand itself. Staatz and others (1980, p. 3–4, and references cited therein) described the mining history of the heavy-mineral beach placers of the northeastern Florida–southeastern Georgia area. Mining ceased in this area in late 1978: increasing environmental regulations made mining operations more costly, which was compounded by steep increases in coastal real estate values. Thus, heavy-mineral concentrations in the modern beaches became much less valuable than the real estate they occupy.

In addition to the modern beach deposits, monazite-bearing sands occur in the raised Pleistocene and Pliocene beach deposits that lie as much as 80 km inland; they are deposits of former shorelines. Relict shorelines, which lie 3–33 m above the sea level, occur in the outer coastal plain region from Maryland to Florida. Thorium exploration in the Eastern United States coastal plain areas can benefit from several aeroradiometric maps that were compiled and interpreted by the USGS (Force and others, 1982; Grosz, 1983; Grosz and others, 1989; Owens and others, 1989).

The monazite and associated heavy minerals in the relict shoreline deposits of the southeastern United States were eroded from crystalline rocks of the Piedmont province (Mertie, 1953), carried towards the Atlantic Ocean by streams and rivers, and eventually redeposited by coastal processes. The natural concentration of heavy minerals in the shoreline area is a multistage process, involving transport by longshore drift, gravity separation by specific gravity and particle size and shape, differential chemical weathering (Neiheisel, 1962), wave action, and, in some parts of the coastal environment, the actions of tides. All of these forces rework the sediments in the shoreline environments through time and naturally concentrate the heavy minerals (see Force, 1991, p. 73–84). The most abundant heavy mineral in the southeastern United States shoreline deposits is ilmenite, in many places forming more than 50 percent of the heavy-mineral fraction. Monazite forms a minor part of the heavy-mineral fraction, usually less than 1 percent. Despite the low concentrations of monazite (and thus, thorium and REE) in the typical coastal placer deposit of the southeastern United States, these deposits have a few distinct advantages as potential sources of thorium: (1) they are relatively easy deposits to excavate (fig. 11); (2) it is relatively easy to separate the heavy-mineral fraction on-site; and (3) these deposits contain multiple salable mineral products.

Figure 11. Heavy-mineral sands dredge in southeastern United States.

Summary

Thorium as a potential source fuel for energy generation has gained new attention in the United States, including consideration in the U.S. Congress (Branan, 2008). Thus, it benefits the United States to recognize and reevaluate its domestic thorium resources (fig. 1). This report summarizes the significant known thorium districts in the United States, and, more importantly, points to the considerable amount of published geologic and resource information that is available from previous studies of these districts. In particular, past studies by the USGS and the former U.S. Bureau of Mines have provided a notable legacy of information on the significant thorium districts and deposits in the United States.

Vein deposits host the largest volume known high-grade thorium resources in the United States. Two thorium vein districts—the Lemhi Pass district of Montana-Idaho and the Wet Mountains area of Colorado (fig. 1)—dominate the known high-grade thorium reserves in the United States (table 2). In recent years, exploration and claim staking of the thorium veins in the Lemhi Pass district has been underway, straddling both sides of the Continental Divide in the district. Average grades of 0.43 percent ThO_2 content in the Lemhi Pass veins, along with similar concentrations of rare-earth oxides, has sparked renewed interest in these vein deposits. Veins and mineralized fractures of similar grade occur in the Wet Mountains area of south-central Colorado; the analysis of 201 vein and fracture samples from this area by Armbrustmacher (1988) revealed average values of 0.46 percent ThO_2, with an average thorium to total-REE ratio of about 2.2:1.

Massive carbonatites, which are rare in the United States, also contain thorium resources (table 1). Examples are the Mountain Pass REE deposit in California and the Iron Hill (Powderhorn) carbonatite complex in Colorado (fig. 1). Because thorium concentrations in these intrusions are low, development most likely would be as a byproduct of the other mineral resources, such as redevelopment of the enormous REE reserves of the Mountain Pass carbonatite deposit (Castor and Nason, 2004). Niobium and REE resources are commingled with the thorium mineralization products in the Iron Hill carbonatite (Van Gosen and Lowers, 2007).

Resistant and dense thorium-bearing minerals, chiefly the mineral monazite, occur in the black sand heavy-mineral concentrations of some stream and beach deposits. These alluvial deposits have been mined in the past by placer methods (sluicing, dredging). Notable examples occur in intermontane stream valleys of Idaho, in stream and river deposits of the Piedmont region of North and South Carolina, and in beach deposits of northeastern Florida–southeastern Georgia (fig. 1; table 1). Whereas alluvial deposits have the lowest thorium concentrations of the thorium deposit types, they do have practical advantages favoring their development, such as relatively low mining costs, easier separation of the heavy-mineral concentrates, and the potential for coproduction of other mineral commodities. Coproducts may include REE in monazite; titanium in ilmenite and rutile; iron in magnetite; zirconium and hafnium in zircon; and industrial-grade garnet, staurolite, tourmaline, kyanite, and sillimanite, salable as abrasives and as refractory minerals.

As interest increases towards thorium as an alternative nuclear energy fuel source, exploration interest will become renewed on the three principal types of domestic thorium deposits—veins, disseminated, and alluvial (placer). The intent of this report is to provide an overview of the significant thorium deposits of the United States, and highlight the breadth of preexisting published information that can be used as a framework for the next generation of thorium exploration in the United States.

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