GEOLOGY AND MINERALOGY OF THORIUM OCCURRENCES

Thorium is the 38th most abundant element in the crust of the earth, averaging about 6 ppm, with the Th/U ratio about 3. It is relatively depleted in mafic rocks (basalts) where the concentration averages about 1 ppm, although alkalic varieties (high Na and K relative to Ca) range up to 5 ppm. Outstanding enrichments are noted in northern Italy where Quaternary alkalic basalts contain 250 ppm Th (Locardi and Mittempergher, 1971). Granitic rocks show a distinct increase over mafic, averaging 20 to 30 ppm. The Conway granite of New Hampshire, a typical example, averages near 60 ppm Th. Alkalic varieties show only a slight enrichment, although thorium deposits show a distinct association with certain alkalic igneous complexes (Bayer, G., and others, 1978, Thorium, in: *Handbook of Geochemistry,* K.H. Wedepohl, ed.)

A distinct geochemical association occurs between thorium and uranium during igneous processes because of their similar ionic size and charge (4+). However, the two elements fractionate during weathering and erosion, because, unlike thorium, uranium oxidizes to U^{6+} to form the very soluble, and therefore mobile, uranyl $(UO_2)^{2+}$ ion. Thorium remains in the refractory solid form and is mostly transported as distinct grains of various minerals. Sandstones contain about 2 ppm Th, with beach sands containing 10 ppm, and limestone averages about 2 ppm. Shale contains 10-15 ppm Th; small amounts of thorium may adsorb to clay particles during weathering. Bauxite contains up to 50 ppm; this material is typically the residual weathering of alkali rocks. Although it will be demonstrated below that thorium reserves are associated with phosphorus-enriched rocks, typical phosphate sedimentary rocks average 1-5 ppm Th. (Bayer, G., and others, 1978, Thorium, in: *Handbook of Geochemistry,* K.H. Wedepohl, ed.)

Because of the large size and high charge of the thorium ion (Th^{4+}) it behaves as an incompatible element during primary fractional crystallization of igneous melts, meaning that it does not exhibit ionic substitution in common rock-forming minerals; quartz and feldspar in common igneous rocks average about 0.5 ppm Th. However, thorium will exhibit an ionic substitution for other incompatible elements of similar size and charge. The most common ore mineral of thorium is monazite $[(Ce,La,Nd,Th)PO_4]$, a common accessory mineral occurring in small amounts, a percent or less, in granites and related igneous rocks. This monazite can contain several percent ThO_2 substituting for light rare earth elements (LREE). Other primary ore minerals of thorium are thorianite $[ThO_2]$ and thorite $[ThSiO_4]$.

Thorium also will substitute for elements with similar size and charge, such as uranium, zirconium and rare earth metals, particularly cerium, in accessory minerals, including but not limited to zircon $[ZrSiO_4]$, euxenite $[(Y,Er,Ce,La,U,)(Nb,Ti,Ta)_2(O,OH)_6]$, allanite $[(Ce,Ca,Fe^{2+})_2(Al,Fe^{3+})_3Si_3O_{12}(OH)$, parasite $[Ca(Ce,La)_2(CO_3)_3F_2]$,and xenotime $[YPO_4]$. Thorium and other incompatible elements show a strong affinity for phosphorous, thus its greater content of thorium in minerals such as monazite compared to other common accessory minerals.

Because of its incompatible behavior, during fractional crystallization of a magma thorium will remain in the melt phase and appear late in the reaction series in granitic rocks, and in pegmatites, the last to form from the melt. Thus it will be rare in basaltic or andesitic rocks. A common origin for granitic magmas is the melting of pre-existing crust in orogenic (mountain-building) belts where geothermal gradients are elevated. Once a melt forms the incompatible elements will prefer to partition into the melt, ultimately resulting in the crystallization of accessory minerals. Alkali igneous and carbonatite occurrences are related in that the magmas form by the partial melting of lithosphere in extensional crustal terrains, and the incompatible elements enter the early-formed melt. Under some circumstances a separate carbonate melt will form, resulting in carbonatites. Rare earth deposits are associated with the latter where the metals occur as complex fluoro-carbonate minerals such as bastnaesite $[(Ce,La)CO_3F]$, often enriched in thorium. The optimum case is where the magma, low in calcium (alkalic) and high in aluminum (peraluminous), forms by melting of only small amounts (approximately 1%) of depleted crust (that which has already been melted previously). This commonly occurs is tectonically rifted areas.

During the evolution of orogenic zones involving volcanism, metamorphism and the intrusion and crystallization of magmas at high temperatures, a separate aqueous phase may form, either as a result of phase separation from the melt, or incorporation of water from the crust proximal to the volcanic activity. Deep in the crust at high temperatures and pressures conditions necessary to confine the fluid, pegmatites will result from the crystallization of coarse mineral assemblages, most commonly feldspar and other rock-forming minerals, but also significant amounts of incompatible accessory minerals, including those containing thorium. Pegmatites were one of the earliest sources of radioactive materials.

Under lower pressure conditions following the formation of an aqueous phase incompatible elements will partition into the aqueous fluid and be transported down a thermal gradient in fractures to form veins. These fluids seem to be compositionally distinct from those responsible for transporting base- and precious-metals responsible for common sulfide veins.

Important reserves of thorium occur as placer deposits in alluvial or marine sediments or sedimentary rocks that consist most commonly of coarse quartz-rich materials. Placer deposits result from the weathering and erosion of rocks exposed at the surface containing heavy minerals. The ultimate source of thorium minerals will be granitic rocks and veins exposed during uplift and erosion. However, during the evolution of coastlines several episodes of remobilization, deposition and enrichment can occur, resulting in mineral contents greater than the original source granites. Manifestations of this process can be observed along common beaches and stream beds, where dark streaks, mostly consisting of common iron minerals, are evident. The development of a heavy mineral placer may not rely on a source rock that is especially enriched in the pertinent heavy minerals, but the proper conditions for weathering of the source together with hydrologic conditions where the grains can be separated according to their physic properties, either by stream action or waves and currents along coast lines.

Enrichment occurs as a result of the unique physical properties of certain minerals, a specific gravity higher than the host sand particles and resistance to physical and chemical breakdown. Monazite has a specific gravity of approximately 5.2, hardness of 5, zircon, specific gravity 4.8, hardness 7.5, depending on their composition, whereas common quartz and feldspar have specific gravities of about 3. Therefore, the nature of the placer deposit is closely related to the energy of the depositional environment (or surface water velocity). Streams must be of sufficient velocity to transport the heavier particles to the environment of deposition (coastal beaches) where the sediments are reworked.

In addition, depending on the degree of weathering, common rock-forming silicates usually break down into a mixture of clay, quartz and hydrated oxides, in contrast to the relatively refractory accessory incompatible element minerals such as monazite, apatite (both phosphates) and zircon. Products of weathering depend on climate, topography and time. It is no coincidence that many marine placers are found in tropical climates adjacent to eroding granite-cored mountain ranges on the trailing edge tectonic plates.

For perspective, the following lists the estimated identified thorium resources (reasonably assured plus inferred) compiled by the World Nuclear Organization (http://www.world-nuclear.org/info/inf62.html) based on a market value of $80/kg Th, in tonnes Th, and percent of world total:

Australia	489,000 t	19 %
United States	400,000	15
Turkey	344,000	13
India	319,000	12
Brazil	302,000	12
Venezuela	300,000	12
Norway	132,000	5
Egypt	100,000	4
Russia	75,000	3
Greenland	54,000	2
Canada	44,000	2
South Africa	18,000	1
Other Countries	33,000	1
World Total	2,610,000 t	

Thus, just six countries contain 83 % of the known thorium reserves.

The U.S. Geological Survey recognizes 347 world-wide occurrences of monazite in 48 countries, including 67 in Australia and 58 in the United States. (http://tin.er.usgs.gov/ree.php?mineral=monazite). The occurrences are classified as (world number of occurrences in parentheses, U.S. in brackets): shoreline placers (167) [9], carbonatite (62) [9]; alluvial placers (39) [13]; alkali igneous (37) [4]; phosphorite (16) [13]; pegmatites and veins (11) [5]; metamorphic (5) [4]. The tabulation does not

include other thorium ore minerals, such as thorianite and thorite which may be more typical of pegmatites, and thorium-bearing rare earth minerals that may occur in carbonatites.

World thorium resources in terms of the types of deposits, in tonnes of Th, and the percent of world total are shown below based on a tabulation from the Australian Mines Atlas: (http://www.australianminesatlas.gov.au/aimr/commodity/thorium.html)

Carbonatite	1,900,000 t	31.3 %
Placer Deposits	1,500,000	24.7
Veins	1,300,000	21.4
Alkalic Rocks	1,120,000	18.4
Other	258,000	4.2

While the total resource does not agree with that of the previous tabulation of identified thorium resources from the World Nuclear Organization, it does give a perspective on the relative importance of the various deposit types.

The following discussion serves two primary purposes: 1) to place the various thorium deposits into an overall petrologic and tectonic framework, allowing for the prediction of yet discovered resources; and 2) to briefly describe the geology of noteworthy examples of thorium deposits.

The geology and genesis of all types of deposits listed above are related, and resource distribution to a certain extent is predictable. Alluvial and shoreline placer deposits rely on a primary source of igneous rocks enriched in accessory minerals containing appropriate incompatible elements, i.e. thorium in monazite. Enriched here may not be any more than several tenths to a percent of the rock mass. Those igneous rocks most enriched will be alkalic (mineralogy high in sodium and potassium and low in calcium) and related carbonatite (rock consisting of carbonate minerals that crystallized from an unusual carbonate melt). A carbonatite is very commonly the last phase to form in the fractional crystallization of an alkalic magma, and as such may represent the center of a concentrically zoned alkalic igneous complex. Pegmatite and vein occurrences result when an aqueous fluid phase separates from a fractionally crystallizing magma, and incompatible elements are partitioned into the fluid phase, from which the minerals will precipitate.

By nature of the plate tectonic process, the margins of continental land masses are characterized by mountain building processes whereby blocks of crust are compressed, during which the rocks are progressively metamorphosed and melted, followed by uplift and erosion. The result will be a block of lithosphere of significant proportions and elevation, of metamorphic rocks with imbedded igneous intrusions, and perhaps related volcanic arcs, on continental margins shedding their debris through streams and rivers, ultimately into the sea. The metals, as refractory mineral grains (resistant to chemical and physical degradation) sourced in various parts of this cycle will be transported during this tectonic cycle, to be variably concentrated, depending on the fluvial energy of the

transporting medium. Thus, it would be expected, and appropriately observed, that fluvial or beach placer deposits of monazite would occur adjacent to igneous and/or metamorphic rocks containing this mineral. If the original continental marine sediments are buried and lithified, the resultant sedimentary rocks may be caught up in the tectonic cycle, metamorphosed and partially melted, and serve as a source of heavy minerals inherited from the original sediment.

In contrast to compressional tectonics characteristic of continental plate margins, alkalic and associated carbonatite complexes develop in areas where the continental crust has experienced tensional forces and rifting has occurred. All major oceanic basins, perhaps with the exception of the Pacific, began with a rifting event. Note the occurrence of alkalic complexes and associated rare-earth (thorium) deposits in East Greenland, representing the opening of the Atlantic Ocean basin. Also, the Rio Grande Rift of North America, and the St. Lawrence River Valley, and many others around the World, represent examples with associated alkalic complexes. In some cases, based on geology, some alkalic complexes developed along orogenic belts where local oblique extension has occurred. Often, the geology of these rifted terrains is characterized by mantle-derived mafic and ultramafic rocks, and alkalic rocks derived by the partial melting of continental crust by rising basaltic magma.

Pegmatites can be the end phase of fractional crystallization of granite magma, or the result of partial melting of the crust during prograde metamorphism. They are classified into two types, simple and complex. The former have a very simple mineralogy similar to the typical granite of feldspar, quartz, and mica, and have little or no exotic thorium accessory minerals. The complex pegmatites are much less abundant, and contain abundant accessory minerals, some thorium- and/or uranium-bearing. The complex varieties show a characteristic mineral zoning, where the thorium minerals occur in one particular zone with other exotic phases. These pegmatites are often characterized by very large crystals; several meters in length not uncommon. More common are minerals a few to several centimeters in size. Igneous pegmatites typically are elliptical to tear-drop shape, narrowing downward into a root zone. Commonly, veins of similar mineralogy cross-cut the pegmatites, however, these veins do not extend far beyond the margins of the pegmatite, and their formation is related to that of the pegmatite, itself. Concentrations of thorium minerals in pegmatites are quite localized and do not constitute volumetrically significant resources.

Metamorphic pegmatites are irregular, vein, or dike-like in shape, and are conformable to the schistosity of the surrounding host rocks. These pegmatites form by the partial melting of rocks as a result of increase in geothermal gradient deep within mountain-building zones, resulting in a mixture of metamorphic and igneous mineral assemblages (migmatites).

A zone of rare-earth and radioactive pegmatites extend northeast to the northwest of and paralleling the St. Lawrence River Valley in southern Ontario, Canada. Over 100 occurrences lay within a metasedimentary assemblage of high grade metamorphic rocks within the Grenville Province, which represents an ancient orogenic zone of late

Precambrian age. Geochemical studies suggest the pegmatites formed about 1020-1050 Ma at temperatures of approximately 550 ^{o}C, suggesting a metamorphic origin (Lentz, 1991). Supporting the metamorphic origin is the lenzoid shape of the pegmatites which roughly conform to the schistosity of the host rocks. Unlike igneous pegmatites, these do not exhibit the well developed zoning, and in gross terms resemble veins rather than igneous dikes. Thorium-bearing minerals include uraninite, thorianite, uranothorite, zircon, and allanite. The thorium content of selected pegmatites ranges up to 5 %, however, most occur in the 0.15 to 0.3 % range.

Staatz (1974) summarizes the characteristics of thorium-containing vein deposits in the United States. Literature on similar occurrences elsewhere suggests the latter exemplifies vein deposits around the world. Thirteen occurrences, all but one in the Rocky Mountain region, are described, where eight of those are associated with alkalic or carbonatite igneous complexes (Hall Mountain, and Lemhi, ID; Powderhorn and Wet Mountains, CO; Laughlin Peak and Capitan Mountains, NM; Mountain Pass, CA, Wausau, WI). Diamond Creek (ID), Gold Hill (NM), Quartzite and Cottonwood (AZ), and Monroe (UT) show no apparent relationship to alkalic igneous activity.

The veins are tabular, and occur in shear zones; some deposits indicate that shearing was contemporaneous with mineralization, resulting in fractured and granulated mineralization. More than one episode of veining is evident in some districts. In many cases the thorium minerals occur in lenses and stringers in more extensive quartz-feldspar-iron oxide veins. Veins range up to 5000 feet long and 50 feet wide. Quartz is by far the most important gangue mineral with minor microcline; calcite is important in some areas.

Some vein occurrences show a spatial relation to carbonatite igneous intrusions, such as the Wet Mountains and Powderhorn, Colorado, and Mountain Pass, California. The Wet Mountains occurrence is characterized by a very unusual alkali mafic and ultramafic layered complex consisting of biotite-hornblende syenite, mafic nepheline-bearing rocks and nepheline sysenite of Cambrian age. Small scattered carbonatite dikes cross-cut the mafic complex and are found in the surrounding Precambrian country rock.

Bokan Mountain in southeast Alaska exemplifies the association of thorium deposits with alkalic igneous rocks. The uranium-thorium deposits are hosted by veins and pipe-shaped bodies in a multiphase circular alkalic granite intrusive complex of late Jurassic age (151 Ma) intruded into Ordovician quartz monzonite and diorite. To date, only uranium has been recovered from 89,000 tonnes of ore averaging 1 % U_3O_8 and 3 % ThO_2 (Staatz and others, 1980; Thompson, 1988) Primary ore minerals are uraninite and uranothorite. Unusual for this type of deposit is the occurrence of about 2 % base-metal sulfides. Important amounts of rare earth elements are also present as bastnaesite, xenotime allanite and monazite. Iron oxides are abundant as hematite, limonite, and minor magnetite. Other accessory minerals are fluorite, zircon, phenacite, pyrochlore, and columbite (Staatz and others, 1980).

At Bokan Mountain the host intrusion consists of riebeckite granite porphyry, aegirine granite porphyry and minor pegmatites, and smaller intrusions, all reflecting the sodium-rich nature of the magmatic system. The intrusions are distributed in a ring-like structure showing successive episodes of emplacement. The veins and pipes occur around the margins of the intrusive complex and appear to be genetically related to the emplacement of the intrusions. The pipes consist of a granite phase, and the ore minerals are disseminated through out the granite and along small micro-fractures in the granite. Veins range up to 2100 feet in length and 10 feet in width, however, most are less than 1 foot in width. Veins can be found up to 18 miles from the igneous complex.

Overall composition and structure of the complex supports the conclusion that the Bokan Mountain complex was emplaced as a closed system where all igneous phases represent periodic intrusion off fractionally crystallizing alkalic magma, and the elements were partitioned into an aqueous phase that separated from the same magma. The temperature of the hydrothermal fluids from which the minerals precipitated was about 400 ^{o}C (Thompson, 1988)

The Cambrian aged alkalic and carbonatite occurrence of the Wet Mountains of central Colorado is a perfect example of the development of rare earth and thorium deposits in an ancient continental rifting setting. The area contains a large mafic to ultramafic layered complex and associated alkalic bodies consisting of mafic nepheline intrusions and nepheline syenite and cross-cutting carbonatite dikes. (nepheline is a feldspar-like mineral commonly contained in alkalic rocks that result from the crystallization of magmas under-saturated with silica. The fractional crystallization of such magmas produces carbonatites) Several hundred thorium-bearing veins occur in a northwest-trending zone, mostly in the surrounding Precambrian country rock. The veins are mostly quartz, carbonate and iron oxides, with minor amounts of barite, fluorite and sulfides, and no clear thorium minerals have been identified, except perhaps thorogummite. The distribution of the thorium is erratic and discontinuous; radioactivity attributed to thorium is highest where limonite is abundant. Thorium concentrations range from 0.02 to 12.5 %; uranium is rare in the veins (Singewald and Brock, 1956; Staatz, 1974).

The Powderhorn occurrence is a Cambrian-aged (570Ma) alkalic complex intruded into Precambrian igneous and metamorphic rocks in southwestern Colorado. Rock units are pyroxenite, uncompahgrite, ijolite, nepheline syenite (all unusual alkalic rocks) and carbonatite. The Iron Hill complex within the pyroxenite represents a significant titanium resource, and consists of magnetite, perovskite ($CaTiO_3$), fluorite, ilmenite, fluoapatite, and titanite. The pyroxenite averages 5.3 % TiO_2, 510 ppm Cerium, 1,240 ppm rare earth elements, and 22 ppm thorium.

At Powderhorn, several hundred carbonatite dikes intrude the pyroxenite, radiating outward from the Iron Hill intrusion. The dikes range upward to 600 feet along strike, with thicknesses between 3 and 5 feet. The carbonatite consists of dolomite, calcite, siderite, iron and base-metal sulfides and oxides, barite, apatite, monazite, and other rare earth minerals. No minerals were found with thorium as an essential element, however, thorium contents range from 0.0035 to 0.361 %, and may be substituted for rare earth

carbonates and phosphates. The carbonatite contains average values of 910 ppm Ce and 1,960 ppm total REE (Staatz, 1974; Staatz and Others, 1980; Van Goosen, 2009).

At Mountain Pass in southeast California, thorium occurs associated with a massive carbonatite body, the Sulphide Queen body, carbonatite dikes, and as thorium veins associated with Precambrian alkalic potassic igneous bodies intruded into metamorphic and igneous rocks. The massive Sulphide Queen body is elongate in the northwest direction, with a length of 2400 ft, and an average width 700 ft, narrowing to the north. It has a roughly dike-like form that dips to the southwest at roughly 40°. The body contains three different rock assemblages; the most common is a grey calcite-barite rock consisting of 40-70 % calcite, 15-50 % barite, and 5 to 15 % bastnaesite, with lesser amounts of quartz, apatite, monazite, thorite, allanite, iron oxides, and base metal sulfides. The average ThO_2 content is 0.01 to 0.09 %. However, samples containing visible monazite have 0.08 to 0.2 % ThO_2.

At Mountain Pass thorium occurs in the rare earth-rich carbonatite dikes that range in thickness from 1 to 20 feet, and are up to 400 feet long. They contain calcite, barite, with or without bastnaesite, with minor amounts of thorite siderite, apatite, iron oxides, and base metal sulfides. The ThO_2 content of the dikes is 0.24 to 2.39 %, and the total REE content is 2.03 to 18.64 %. Thorium veins are irregular, lenticular and discontinuous, dip steeply to the southwest at angles of 60 to 80°, and occupy northwest-trending shear zones, conformable to most other structures in the district. They have thicknesses ranging from 1 in. to 12 ft. The veins consist of major quartz and microcline, with minor calcite, thorite, and bastnaesite. Allanite, monazite and iron oxides also occur. The ThO_2 content of the veins ranges from 0.03 to 6 %, and REE content from 1.96 to 8.94 % (Staatz, and others, 1979; 1980).

The Lemhi district represents a major thorium resource where mineralization occurs in veins. The veins consist of mostly quartz and occupy primarily northwest-trending steeply-dipping shear zones in quartzite and finer grain metamorphic rocks of the Precambrian Belt Supergroup. In many cases the veins occur as small en echelon structures within a major through-going shear zone up to 6000 feet in length. The mineralogy of the veins consists of quartz, feldspar, hematite, secondary limonite, with minor calcite and siderite. Thorium appears to be concentrated in the iron-rich portions; the most common ore mineral of thorium is thorite, with lesser amounts of monazite. Brockite, a calcium thorium phosphate, constitutes the principal ore mineral in at least one vein system. Small amounts of thorium-bearing rare-earth minerals also occur as well as xenotime, and allanite. The ThO_2 content of thorium veins range from 0.0008 to 9.4 %.

Alluvial placers of monazite occur on the Coastal Plain of the southeastern United States in stream valleys that cut a series of Pleistocene gravel terraces with headwaters in the crystalline core of the Appalachian Mountains to the west. Other heavy minerals occurring in the placers are ilmenite and magnetite with lesser amounts of garnet and zircon. Monazite grades range from 2 to 43 kg/m^3, with a mean of 9 kg/m^3. The monazite content decreases down stream and only minor amounts are found in the modern beach sands, with the exception of northern Florida. The monazite content of the modern stream

valleys is highest proximal to ancient stream valleys within the Cretaceous and Tertiary sedimentary sequence of the Coastal Plain, suggesting multiple episodes of transport and deposition throughout the history of uplift of the Appalachian Mountains (Mertie, 1975).

The crystalline rocks in the Appalachian Mountains exhibit three zones of enrichment of monazite; similar rocks outside this region do not contain equivalent concentrations of this accessory mineral. It is thought that the monazite-bearing rocks inherited their chemical character from the Precambrian basement that consists of metamorphosed sedimentary assemblages which represent original stream valleys in a Precambrian terrain in which ancient alluvial placers formed. The monazite in the modern streams could be relic phases from the originally placers, or could have been reformed during intervening episodes of metamorphism and igneous activity (Mertie, 1979). This same scenario may be repeated around the world along eroding coastlines characterized by multiple episodes of mountain-building and metamorphism, volcanism, and sedimentation.

Alluvial placers occur in central Idaho along the west margin of the Idaho Batholith, a very large granitic intrusive complex that occupies much of the center of the State. Eleven separate alluvial districts occur. Although monazite has been recognized in over 100 streams, only three areas are significant to constitute economic resources. The heavy mineral content of the placers ranges from 0.1 to 1 % and averages 0.5 %. The ThO_2 content of the monazite ranges from 2.2 to 6.2 %. Historically about 300 tons of ThO_2 were recovered from roughly 7000 tons of monazite concentrate from about 12 M tons of dredged gravel (Staatz and others, 1980).

These Idaho placers occur in incised stream valleys and in alluvial basins eroded into the Idaho Batholith and surrounding rocks. The former is assumed to be the source of the monazite and other heavy minerals. Other thorium-bearing minerals in the source rocks are euxenite and uranothorite. Typically, the monazite content decreases down-stream from the source. Although the depth and form of the placers vary, the best areas are where erosion and deposition was controlled by on-going faulting. In the Long Valley area, one of the most productive, faulting was episodic into the Pleistocene, and several thousand feet of monazite-containing gravel was deposited, although recovery only went to less than 200 feet. The most common placers ranged from a few tens up to a hundred feet (Staatz and others, 1980). The gravels typically consist of coarse quartz, feldspar and rock fragments of bedrock, typical of stream bed material in mountainous areas.

The most abundant mineral in the placers is ilmenite, ranging up to 95 %. Monazite makes up about 16 % of the heavy minerals in the placers with uranothorite 1 %, and euxenite 0.5 %. Other minerals in the heavy mineral fraction are zircon, pyrite, hematite, rutile, cassiterite, allanite, columbite, topaz, garnet, xenotime and gold.

Enrichment of heavy minerals along shorelines is a continuous process involving the sorting by long shore currents where grains are separated according to their size and specific gravity during wave action within the tidal zone. The heaviest and largest grains will be concentrated where the energy is the highest. The initial deposition will occur at the estuaries of rivers responsible for supplying the material. The latter will subsequently

be transported along the shoreline, continually being worked by wave action. The result will be shoreline-parallel bars or dunes containing streaks of heavy minerals. The latter will be constantly moved during beach destruction and renewal during storm and climatic events.

Local enrichments of monazite, up to 2 % occur in Pleistocene to modern beaches of northern Florida. Ilmenite, zircon, and rutile usually dominate the heavy mineral content (Staatz, 1980). Monazite was recovered as a by-product of titanium production. The ThO_2 content of the raw sand is estimated to be 0.0003 to 0.04 %. Titanium sands are common around the world, but monazite is not always present, and may depend on being able to identify the appropriate source terrain.

Particularly high grade but small concentrations of monazite occur along the east coast of Sri Lanka in the Indian Ocean (Overstreet, 1967). Heavy mineral streaks are constantly forming along the beaches as a result of seasonal changes in wave and current action. Here heavy mineral deposits may contain up to 50 % monazite, averaging 15%. Monazite concentrates contain nearly 9 % ThO_2. Deposits occur as constantly migrating off-shore bars within low energy water embayments.

SELECTED BIBLIOGRAPHY ON THORIUM OCCURRENCES

Andreoli, M.A.G., C.B. Smith, M. Watkeys, J.M. Moore, L.D. Ashwal, and R.J. Hart, 1994, The geology of the Steenkampskraal monazite deposit, South Africa: Implications for REE-Th-Cu mineralization in charnockite-granulite terranes: *Economic Geology,* v. 89, p. 994-1016.

Bayer, G., J.J.W. Rogers, J.A.S. Adams, and U.K. Haack, 1978, Thorium, in: *Handbook of Geochemistry,* K.H. Wedepohl, ed.

Bea, F., 1996, Residence of REE, Y, Th, and U in granites and crustal protoliths; Impications for the chemistry of crustal melts: *Journal of Petrology*, v. 37, p. 521-552.

Christman, R.A., M.R. Brock, R.C. Pearson, and Q.D. Singewald, 1960, Geology and thorium deposits of the Wet Mountains, Colorado – a progress report: U.S. Geological Survey, Bulletin 1072-H.

Lang, A.H., et al., 1962, Canadian deposits of uranium and thorium, 2nd ed.: Geological Survey of Canada, Economic Geology Report 161; 324p.

Lentz, D. R., 1991, Radioelement distribution in U, Th, Mo, and rare-earth-element pegmatites, skarns, and veins in a portion of the Grenville Province, Ontario and Quebec: *Canadian Journal of Earth Science*, v. 28, p. 1-12.

Locardi, E., and M. Mittempergher, 1971, Exhalative supergenic uranium, thorium and marcasite occurrences in Quaternary volcanites of central Italy: *Bulletin Volcanologique*, v. 35, p. 173-184.

Long, K.R., B.S. Van Gosen, N.K. Foley, and D. Cordier, 2010, The principal rare earth element deposits of the United States – A summary of domestic deposits and a global perspective: U.S. Geological Survey, Scientific Investigations Report 2010-5220, 100p.

Mackin, J.H., and D.L. Schmidt, 1956, Uranium- and thorium-bearing minerals in placer deposits in Idaho: U.S. Geological Survey, Professional Paper 300, p. 375-380.

McLemore, V.T., 1983, Uranium and thorium occurrences in New Mexico: distribution, geology, production, and resources; with selected bibliography: *New Mexico Bureau of Mines and Mineral Resources, Open File Report OF-183*; 950p. U.S. Department of Energy Report GJBX-11 (83).

Mertie, J.B., 1975, Monazite placers in the southeastern Atlantic states: U.S. Geological Survey, Bulletin 1390; 41p.

Mertie, J.B., 1979, Monazite in the granitic rocks of the southeastern Atlantic States – an example of the use of heavy minerals in geological exploration: U.S. Geological Survey, Professional Paper 1094; 79p.

Overstreet, W.C., 1967, The geological occurrence of monazite: U.S. Geological Survey, Professional Paper 530; 327p.

Page, L.R., H.E. Stocking, and H.R. Smith, eds., 1956, Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on peaceful uses of Atomic Energy, Geneva, Switzerland 1955: U.S. Geological Survey, Professional paper 300; 737p.

Singewald, Q.D., and M.R. Brock, 1956, Thorium deposits in the Wet Mountains, Colorado: U.S. Geological Survey, Professional Paper 300, p. 581-585.

Staatz, M.H., 1974, Thorium veins in the United States: *Economic Geology*, v. 69, p. 494-507.

Staatz, M.H., 1979, Geology and mineral resources of the Lemhi Pass thorium district, Idaho and Montana: U.S. Geological Survey, Professional Paper 1049-A; 90p.

Staatz, M.H., and others, 1979, Principal thorium resources in the United States: U.S. Geological Survey, Circular 805, 42p.

Staatz. M.H., R.B. Hall, D.L. Macke, T.J. Armbrustmacher, and I.K. Brownfield, 1980, Thorium resources of selected regions in the United States: U.S. Geological Survey, Circular 824; 32p.

Thompson, T.B., 1988, Geology and uranium-thorium mineral deposits of the Bokan Mountain Granite complex, southern Alaska: *Ore Geology Reviews*, v. 3, p. 193-210.

Van Gosen, B.S., 2009, Iron Hill (Powderhorn) carbonatite complex, Gunnison County, CO – A potential source of several uncommon mineral resources: U.S. Geological Survey Open File Report OF2009-1005; 28p.

Revised August 22, 2012