Alaska’s rare earth deposit and resource potential
by James C. Barker and Bradley S. Van Gosen

Alaska’s known mineral endowment includes some of the largest and highest grade deposits of various metals, including gold, copper and zinc. Recently, Alaska has also been active in the worldwide search for sources of rare earth elements (REE) to replace exports now being limited by China. Driven by limited supply of the rare earths, combined with their increasing use in new ‘green’ energy, lighting, transportation, and many other technological applications, the rare earth metals neodymium, europium and, in particular, the heavy rare earth elements terbium, dysprosium and yttrium are forecast to soon be in critical short supply (U.S. Department of Energy, 2010).

The REE, accompanied by other high field strength metals (such as Nb, Zr, Ti, Th, W), are associated with alkaline complexes of the Hogatza Belt in northwest Alaska; peraluminous tin-granites of the Ruby batholith in central Alaska and the Porcupine plateau in the northeast; and peralkaline intrusive complexes in the southwest Alaska Range west of Anchorage, and on Prince of Wales Island in southeastern Alaska. Limited evidence suggests that the heavy REE are associated with deposits that became more highly evolved by late hydrothermal processes.

The first exploration specific to REE in Alaska began in 2007 at Bokan Mountain in southeast Alaska. By the summer of 2011, at least half a dozen properties across Alaska were being explored. The first 43-101 compliant resource was announced for the Dotson Ridge deposit at Bokan Mountain in early 2011; ongoing drilling continues to upgrade that resource. The deposits of the Bokan Mountain district are particularly enriched in the heavy REE. Potential development of these deposits benefits from direct access via sheltered tidewater.

The search for neodymium, plus heavy rare earth elements such as terbium and dysprosium, are the present-day ‘Eureka Gold Rush’ of Alaska. That search has been particularly intense in places such as northeastern Canada and Canada’s Northwest Territories, Greenland and Alaska.

The reopening of California’s Mountain Pass Mine by Molycorp Inc. will help meet demand for the light rare earth elements (LREE) (Fig. 1) and, most importantly, help supply the need for neodymium, which occurs in this bastnäesite-rich carbonatite orebody. However, there are only a handful of known significant sources worldwide of the heavy REE (HREE), which include elements gadolinium through lutetium, plus yttrium. Consequently, exploration is beginning to define REE deposits on their content of the HREE as a percentage of the total REE (TREE) content. Because of the anticipated crisis to locate sources of REE, specifically the heavy rare earth elements dysprosium, terbium and yttrium, this article will make specific mention of the concentration of HREE discovered in some exploration projects in Alaska.

Traditional uses of REE have included catalysts in petroleum, alloys in steel, and phosphors in fluorescent lighting. The 21st century has witnessed a new world of REE uses, most conspicuously in advanced green technology and defense applications. Lightweight rare earth magnetic materials are expected to power a new generation of electric vehicles, which require REE-metal hybrid batteries. Solar panels, highly efficient wind turbine generators, and LED lighting will increase REE demand. Demand could also rise from a host of new applications presently in research and development laboratories.

As a result of decades of aggressive, global acquisitions and marketing, China has become a “vertically integrated” industrial base. China owns a substantial portion of the world’s known REE resources, performs 100 percent of the world’s...
secondary processing of REE ores, and produces 95 to 97 percent of the world’s REE products (Pui-Kwan, 2011). China has recently restricted export of processed REE ores, particularly the HREE, with the intent to use REO production for internal use and to export only finished products (Pui-Kwan, 2011). Industries in the West as well as in Japan and Korea are presently almost entirely dependent on imported raw REE supplies, potentially leaving thousands of jobs at stake. The demand growth curve is accelerating and the reality is that there is no current significant REE production outside of China. In late 2010, the U.S. Department of Energy (DOE) released a report (U.S. Department of Energy, 2010) warning the U.S. government, defense agencies and western manufacturers of the pending shortages of REE supply. According to Roskill Information Services, the world demand for REO is expected to exceed 200 kt (220,000 st) by 2015 (Table 1).

The geology of REE deposits

The REE are among a group of elements sometimes referred to as the high-field strength elements (HFSE). These are elements of high valency (greater than 2) that are not readily incorporated into the lattice of common rock-forming silicate minerals. Besides REE, these elements also include yttrium, niobium, zirconium, hafnium, tungsten, phosphorus and titanium. Some researchers also include other lithophile elements, such as tantalum, scandium and thorium. These HFSE are associated, as incompatible ions, within alkaline igneous melts that form from low degrees of partial melting in the upper mantle. Their emplacement is often controlled by deep-seated sutures or failed rift zones that reached down to the mantle; consequently, deposits of HFSE in alkaline rocks often occur along structural features and terrane boundaries. Alkaline intrusions include carbonatite, lamprophyre, syenite, feldspathic rocks, kimberlite and related rock compositions. For the most part, these rocks have silica under-saturated compositions, often with unusual mineralogy, including feldspathoids, alkali-pyroxene and alkali-amphibole minerals. (The geology, mineralogy and chemistry of the rare earth elements are summarized in Long and others (2010) and references cited therein.)

Rocks are further classed as peralkaline if their Na + K contents exceed Al content. They are often silica saturated granites and can feature extreme fractionation at progressively higher levels and corresponding lower temperatures within the crust. The HFSE, including REE, are further concentrated by their inherent incompatibilities, resulting in extreme fractionation in the crust; such concentration can lead to economic enrichments. It is generally believed these fractionated peralkaline intrusions represent water-bearing crustal contamination of otherwise dry alkaline

The periodic chart of the elements from the view of a REE exploration geologist.

Table 1

2015 Global forecast supply and demand for rare earth elements oxide (REO) (data from Roskill Information Services, 2010).

<table>
<thead>
<tr>
<th>Rare Earth Element as oxide</th>
<th>2015 demand 180,000 t/a</th>
<th>2015 supply 208,500 t/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerium oxide</td>
<td>63–68,000 t/a</td>
<td>80–85,000 t/a</td>
</tr>
<tr>
<td>Neodymium oxide</td>
<td>35–40,000 t/a</td>
<td>30–35,000 t/a</td>
</tr>
<tr>
<td>Europium oxide</td>
<td>725–775 t/a</td>
<td>575–625 t/a</td>
</tr>
<tr>
<td>Terbium oxide</td>
<td>450–500 t/a</td>
<td>375–425 t/a</td>
</tr>
<tr>
<td>Dysprosium oxide</td>
<td>2,500–3,000 t/a</td>
<td>1,600–2,000 t/a</td>
</tr>
</tbody>
</table>

Note: A surplus supply of cerium is expected to occur because it is produced as a coproduct of neodymium production. In contrast, acute shortages are expected for the heavy rare earths.
silica-poor melts that contain elevated amounts of HFSE along with volatiles, particularly F, Cl, CO₂, and SO₄. The consequent hydrothermal influence due to crustal contamination in the peralkaline granites appears to be responsible for the increased favorability of these rocks to produce rare metal deposits. While initial magmatic concentrations of HFSE are primarily the product of crystal fractionation, there is the possibility of an important genetic link between the HFSE enrichment and later hydrothermal alteration. A possible link between HFSE enrichment and late hydrothermal activity is a continuing debate (Salvi and Williams-Jones, 2005). Most researchers agree that silica-under-saturated alkaline rocks and peralkaline silica-saturated rocks within a single intrusive complex are related to a common source, but they have experienced a different genesis (Salvi and Williams-Jones, 2005).

In some settings, REE mineral deposits exhibit both late-stage magmatic and early hydrothermal characteristics; for example, albitization, silicification or propylitic-style alteration may be present. It is apparent that some of the REE occurrences in Alaska are products of hydrothermal processes that enriched the concentrations of HREE, as measured by lower La+Ce/Y ratios (La+Ce representing the light REE, with Y representing the HREE). In more evolved alteration processes, we note that this ratio is markedly lower. For instance, a Ce-La-Nd-rich carbonatite may have a La+Ce/Y ratio of more than 100, whereas a Y-HREE hydrothermal vein may have a ratio less than 1.

In addition to the alkaline host rocks, some calc-alkaline complexes, particularly peraluminous granite complexes (including “tin granites”), are known to contain enrichments of REE minerals. These calc-alkaline complexes can contribute commercially valuable deposits (especially alluvial deposits) of cassiterite, monazite, xenotime, zircon, ilmenite-anatase, wolframite and other related accessory minerals. These minerals can occur as accessories in a crystalline matrix, or as products of high-temperature hydrothermal alteration, especially in greisens, tin-bearing zones, and upper-level alteration zones of molybdenum porphyries.

Light REE and heavy REE

Meeting the new technology demands poses a specific challenge to the exploration and mining industries. While the search is on for new sources of REE, it should be understood that there are essentially two separate but parallel worldwide mineral exploration ventures. Most light rare earth elements (LREE) will be produced from carbonatite deposits in which the ore minerals are primarily bastnäesite, parasite and some local concentrations of monazite. These carbonatite-hosted deposits are typified by Bayan Obo in China (Wu, 2008; Xu et al., 2008; Yang et al., 2009), Mountain Pass in California (Castor, 2008) and the parasite-bastnäesite deposits at Mount Weld (Lynas Corp. Ltd., 2011) and Brockman (Taylor et al., 1995a and 1995b) in western Australia. Production decisions are soon expected from...
Lynas Corp., which is exploring Mount Weld. Molycorp Inc., owners and operators of the Mount Pass deposit, announced that this mine reopened for REE production in December of 2010. Production of REE may also occur in the future by Rare Element Resources, Inc., owners of the Bear Lodge deposit in Wyoming (http://www.rareelementresources.com/s/Home.asp). Generally, it can be assumed that these large deposits will meet most projections of the need for LREE, including neodymium (Nd). However, in order to produce the forecasted Nd demand, these mines may at the same time produce more cerium, lanthanum and praseodymium than is required by the present market demand. Furthermore, carbonatite deposits contain only trace amounts of the HREE.

The supply of sufficient HREE to meet the growing world demand is a separate and unresolved issue compared to the development of LREE deposits, although most HREE-bearing deposits will also contain some of the LREE group. Deposits containing HREE as their primary product or coproduct will probably need to be developed to meet the expected demand. Otherwise, it may severely affect the ability of the western world to employ some of the new environmentally friendly technological developments. Based on the expected geological characteristics, deposits containing HREE tend to be smaller and lower grade than the LREE deposits. However, the HREE, based on unit value, can be more valuable. Because of the higher unit value, HREE deposits of seemingly very low grade, such as the south China ion-absorption clay deposits (some are mined at grade of 0.03 percent total REE), may still be exploitable if the HREE can be mined, recovered, and chemically separated at low-enough cost. At several Canadian properties, such as Kipawa, a cutoff grade of 0.016 percent Dy is proposed (Aurizon Mines Ltd, 2011). The HREE exploration projects at Strange Lake on the Labrador-Quebec border, the Red Wine deposit in Quebec, Thor Lake in Northwest Territories and Bokan Mountain, Alaska, have received the most attention. There are technical and logistical pros and cons that apply to each prospective deposit. For a deposit to be successful, the realities of mining-friendly jurisdictions have become a factor, as have access issues as well as amenable metallurgy and mining costs.

**Alaska’s role in the search for REE**

Alaska hosts notable world class mineral deposits of many minerals. Though there are currently no known major LREE carbonatite discoveries in Alaska that would be similar to the Mountain Pass deposit, a significant yttrium-heavy rare earth element resource is known at Bokan Mountain on Prince of Wales Island (Fig. 2). Numerous other rare earth prospects and occurrences across Alaska are summarized in the following sections.

A review of known REE deposits in Alaska by the authors revealed that igneous-metamorphic terranes of Alaska are particularly favorable for localizing REE-enriched mineralization (Barker, 1990a; Long et al., 2010). Specific to the general favorability of HFSE, including the REE, there are several prominent terranes in Alaska that contain alkaline and peralkaline rocks with known REE occurrences, zircon, niobium, uranium and thorium. Peraluminous rocks of the Ruby Geanticline and Porcupine Plateau are associated with tin (in cassiterite), REE (in monazite and xenotime) and tungsten (in wolframite and scheelite). Only a few of these provinces have been examined in detail. In the 1950s and 1960s, reconnaissance surveys by the USGS and Atomic Energy Commission (AEC) inventoried heavy minerals occurring in placer concentrates, using REE-bearing minerals as an indicator of prospective areas for U-Th mineralization. During the 1970s and 1980s, the National Uranium Resource Evaluation (NURE) program conducted surficial sampling across Alaska and contracted specific studies of some promising sites for uranium. At the same time, the USGS made considerable effort to expand basic 1:250,000-scale geological mapping of Alaska and began regional assessments of mineral commodities. In the 1980s, the U.S. Bureau of Mines targeted the rare earth elements as part of a strategic assessment of critical metals in Alaska; preliminary resource potential estimates were compiled for several prospects, including Bokan.

| Table 2 |

Inferred resource estimates by varying cutoff grade for the Dotson dike system, Bokan Mountain, Alaska.

<table>
<thead>
<tr>
<th>% TREO Cut-off</th>
<th>Tonnes</th>
<th>% TREO</th>
<th>HREO/TREO</th>
<th>Contained TREO (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>1,021,000</td>
<td>1.054</td>
<td>36.80%</td>
<td>23,718,000</td>
</tr>
<tr>
<td>0.7</td>
<td>1,549,000</td>
<td>0.951</td>
<td>37.70%</td>
<td>32,467,000</td>
</tr>
<tr>
<td>0.6</td>
<td>2,489,000</td>
<td>0.834</td>
<td>39.60%</td>
<td>45,751,000</td>
</tr>
<tr>
<td>0.5</td>
<td>3,669,000</td>
<td>0.746</td>
<td>38.60%</td>
<td>60,325,000</td>
</tr>
<tr>
<td>0.4</td>
<td>5,276,000</td>
<td>0.654</td>
<td>40.00%</td>
<td>76,049,000</td>
</tr>
<tr>
<td>0.3</td>
<td>6,126,000</td>
<td>0.613</td>
<td>40.80%</td>
<td>82,765,000</td>
</tr>
<tr>
<td>0.2</td>
<td>6,702,000</td>
<td>0.58</td>
<td>41.30%</td>
<td>85,673,000</td>
</tr>
</tbody>
</table>

* All intercepts with a true width of less than 1.5 m were diluted to a potential minimum mining width of 1.5 m.
Mountain, Dora Bay, Ray River and Kanuti-Kilolitna Rivers.

More recently, in 2010, the USGS addressed the availability of REE in the United States with a chapter on Alaska specifically addressing the geology and REE deposits of Bokan Mountain (Long et al., 2010).


REE in Alaska have been discovered and noted by industry in conjunction with other exploration, primarily uranium. For example, the Mt. Prindle-Roy Creek uranium-thorium prospect was found to contain as much as 20 percent total REE, primarily as LREE (author’s data). Bokan Mountain was the site of a former uranium mine.

REE minerals were first identified in this district in the course of USGS mapping (Staatz, 1978). In 2007, in the first advanced exploration by industry, Ucore Rare Metals Inc. acquired the Bokan Mountain property and began a drill evaluation program. A later section of this paper describes lesser known REE prospects. By 2011, Hinterland Resources had acquired REE prospects within a peralkaline complex in the southwestern part of the Alaska Range, and Cotango Ore Co. and Landmark Alaska LP staked ground in areas of the Melozitna River, Ray Mountains and southern Prince of Wales Island.

An advanced exploration project in Alaska

Bokan Mountain project. Several exploration-stage REE properties have been staked in central and western Alaska and several more have been drilled in the past, primarily to evaluate their uranium content, but only the Bokan Mountain project has been explored adequately for a reportable REE resource estimate to be issued. Ucore Rare Metals, in March 2011, released its first Canadian Securities Administrators compliant National Instrument (NI) 43-101 inferred resource (Table 2), based on results of drilling between 2007 and 2010 on its 100 percent-owned Bokan Mountain project.

The drill-defined mineral resource at Bokan Mountain is located within the Dotson and I&L prospects (Fig. 3). The defined resource is open at depth. In 2011, the company pursued higher-density diamond drilling in order to upgrade the resource estimate in Table 2 (www.ucore.com). Mineralogical and metallurgical research has also been initiated. Ucore holds more than 500 mining claims in the district, including all known prospects. The claims lie within the National Forest Service “Kendrick Bay Minerals Prescription” area, which is designated for mineral development.

In the 1980s, the U.S. Bureau of Mines, as part of the strategic and critical minerals program, identified significant resource potential in the district for REE, Y, Nb, Ta and Zr (Barker and Mardock, 1988; Warner and Barker, 1989). Although not economic at the time, the Bureau
of Mines estimated a strategic resource of 170 million kg (374 million lbs) of combined yttrium and rare earth oxide including the Dotson vein (Note: Historic estimate only, calculated prior to NI 43-101 stipulations).

Mineralization at Bokan Mountain crops out at tidewater on Kendrick Bay in southern Prince of Wales Island, about 60 km (37 miles) southwest of Ketchikan (Fig. 3). The intrusive complex is a highly fractionated, concentrically zoned, Jurassic-age peralkaline granite derived from volatile-rich upper mantle and deep crustal melts (Thompson et al., 1980; Gehrels, 1992; MacKevett, 1963; Staatz, 1978). A riebeckite-rich porphyry central zone is comprised of fine-grained riebeckite granite, surrounded by older successive phases of aegirine-riebbeckite granite and aegirine granite (Fig. 3). Outboard is a border zone of riebeckite-albite-zircon pegmatite with magnetite and aegirine alteration of riebeckite; further outboard are localized bodies of aplite-pegmatite bodies. Surrounding the intrusive complex is a several-km-wide aureole of albitionization.

There are at least 25 known REE occurrences surrounding Bokan Mountain (Warner and Barker, 1989). REE mineralization of mappable scale occurs as a series of concentrically zoned REE-bearing pegmatites cutting the central apex of the intrusion; as subparallel vein-dikes that extend as much as 6 km (3.7 miles) into country rock on either side of the intrusion (these vein-dikes contain most of the known REE resource); and as structurally controlled, shear-hosted mineralization, which includes the past U production from the Ross Adams Mine and at least one example of Ca-metasomatic mineralization.

- Zoned pegmatites are best represented at the IL & M prospect (Fig. 3, site 14) on the south-facing upper slope of the mountain. Flow-banding features indicate that the pegmatites formed during the latest stage of crystallization. Pegmatite bodies up to 10-m- (33-ft-) wide and 100-m-(330-ft-) long can be traced to the summit of Bokan Mountain. The core zones of the larger bodies can contain in excess of 5 percent TREE with a La+Ce/Y ratio of about 1.
- Individual vein-dikes occur in closely spaced sets a few mm- to 50 cm (19 in.) wide, or as single dikes individually 40 cm (16 in.) to several meters thick. All dip steeply, mostly north. The vein-dikes exhibit late magmatic to early hydrothermal characteristics and they form a pegmatic texture most commonly nearer the Bokan Mountain granite intrusion and at higher elevations. The vein-dike structures contain most of the known REE-Y, Nb and Zr resources, including the recently announced inferred resource estimate for the Dotson prospect (Table 2). An overall La+Ce/Y ratio of 1.6 is based on drill intercepts from only the Dotson vein-dike. The Dotson system is one of several vein-dike prospects on the southeast side of Bokan Mountain (Figs. 3 and 4); all display La+Ce/Y ratios of 1.4 to 1.6. At least one more vein-dike system is known to the north of the Bokan Mountain intrusion. An isolated group of lower grade pegmatite and vein-dike structures crops out about 1 km (0.62 miles) south of the Bokan Mountain granites, possibly representing a satellite stock connected to the Bokan Mountain intrusion at depth.
- Shear zone-controlled mineralization in the district includes the Ross Adams uranium deposit (Fig. 3, site 20). Here,
uranothorite, uranoanthorianite and uraninite occur in hematized and chloritic micro-fractures within a pipe-like body that averages about 7-10 m (23-33 ft) in diameter. The deposit was explored for 350 m (1,150 ft) along a plunging, southerly dip bounded by aegirine-riebeckite granite, quartz syenite and overlain by riebeckite porphyry. Mining of the Ross Adams occurred intermittently between the late 1950s and 1971, at which time contract obligations to the Atomic Energy Commission were fulfilled. The average ore grade was reportedly 0.76 percent U$_3$O$_8$ (Warner and Barker, 1989), which is among the highest grade U ore ever mined in the United States. The mine operator in 1980 — Standard Metals — reported that lower grade, unmined material is 0.17 percent U$_3$O$_8$ in an estimated 330 kt (364,000 st) of rock peripheral to the core zone (Standard Metals, 1980); this rock also contains an unquantified content of HREE (Note: This is an historic estimate only.)

- At the Wennie prospect (Fig. 3, site 13), propylitic alteration surrounds a closed structural zone of steep north- and south-dipping faults. Variable mineralization occurs across a 20-m (65-ft) rock exposure. The average of 12 samples across the prospect was 1.36 percent TREE, in which 92.4 percent is HREE yielding a La+Ce/Y ratio of 0.06, indicating an extreme bias of the HREE to TREE. At the Boots prospect, randomly oriented narrow shear zones over a 75-m (246-ft) zone contain low grade mineralization but with a similar very low Li+Ce/Y ratio. Elsewhere, intensely altered shear zones normal to the margin of the intrusion occur along the north and east perimeter of the intrusion; these zones are unevaluated.

- The Sunday Lake prospect (Fig. 3, site 12) is a high-grade REE occurrence (drill intercept of 1.83 percent TREE over 4.8 m or 15.7 ft) that is apparently structurally controlled, which occurs within aegirine granite near an irregular contact with hornfels. High-grade REE material, dominated by HREE (La+Ce/Y of 0.18) and by REE-bearing carbonate minerals, continues to unknown depth but drilling shows mineralization to be closed along strike.

- Metasomatic fluorite-REE-molybdenum mineralization occurs in bodies of unknown size and mineralogy within hornfels shale and black carbonate on the southwest contact of the Bokan Mountain intrusion (Fig. 3, site 17). The mineralization is variably radioactive. Analyses from nine samples indicate 0.1 to 0.55 percent REE+Y and trace amounts to 0.12 percent molybdenum. Samples give a La+Ce/Y ratio of 0.88.

- Mineralogical examinations of Bokan Mountain deposits have identified more than 20 REE-Y, Nb, U-Th-bearing minerals, including fluorocarbonates, oxides, silicates and phosphates in a groundmass of albite, quartz, minor aegirine, and minor to accessory zircon, chlorite, fluorite, magnetite, calcite and iron-lead-zinc sulfides. The dominant REE minerals are kainosite, apatite, allanite, xenotime, bastnaesite, parasite, brennerite, thalenite, imorite, fergusonite, synchysite (Y), and monazite associated with locally intense silicification, albitization, hematitization and chloritization.

Alaska REE exploration and resource potential

Hogatza Plutonic Belt. A belt of Cretaceous alkaline complexes form a 450-km- (280-mile-) long trend in northwest Alaska known as the Hogatza Plutonic Belt (Fig. 2). The belt contains monzonite,
Granodiorite, syenite and nepheline syenite, which form igneous complexes at Indian Mountain, Zane Hills, Purcell Mountain, Selawik region, Peace River, Granite Mountain and Kachaulic. Alkali feldspar dikes locally cut these complexes. Radioactive minerals and REE are known to occur in gold placer workings in the region; some uranium exploration occurred here during the 1970s (Jones, 1977).

**Zane Hills.** Dredge concentrates from Hogatza River contain uranothorianite, allanite and monazite. A composite sample collected by the author contained more than 2 percent REE of which 1.73 percent is Nd. Prospectors in the 1970s located and drilled several sets of thorium-rich vein-dikes in the uplands along the margin of the alkaline rocks. Mineralization includes early-stage hydrothermal breccias with banded layering composed of chlorite, calcite, hematite, amphibole, zircon and magnetite. Fluorite and Pb-Zn-Mo-sulfides are present. Uranothorianite, thorianite, gummite (altered uraninite), betafite, thorite, monazite, allanite, pyrochlore and xenotime were identified by scanning electron microscopy. At the Boston Ridge prospect, as much as 1.2 percent REE occurs in veins. Similar mineralization is found at the Santa Marie (Fig. 4) and Potato Saddle prospects, where more highly evolved hydrothermal veins contain up to 0.5 percent Y and have a La+Ce/Y ratio averaging 0.38, indicating a high concentration of HREE (total REE analyses are not available). The Zane Hills have been described by Miller and Elliott (1977) and Barker (1991a).

**Selawik Hills.** The Selawik Hills complex (Fig. 2), nearly 75 km (46 miles) across, is composed of quartz monzonite, nepheline syenite, syenite and minor pyroxenites. Numerous lamprophyre and alkaline dikes are present near mineral occurrences. Thorium-U-REE-Nb-F mineralization is associated with a hornblende syenite phase locally altered with chlorite, epidote, quartz and fluorite. Mineralization is best exposed in the VABM Saturday area, controlled by numerous hematite-rich fracture and shear zones containing xenotime, zircon, thorianite and an unidentified Nb-U-Ti mineral. Locally, there are fluorite-cemented breccias. The occurrences have been explored by a series of drill holes, but no records could be located. Similar mineralization was also found in the Selawik Lake syenite and nepheline syenite complex. The Selawik Hills intrusions, including the Inland Lake and Selawik Lake complexes, are likely connected at depth (Patton and Miller, 1968; Miller, 1972; Barker, 1985).

**Kachaulic.** This pluton, composed of granodiorite, monzonite and syenite, forms the southwest extent of the Hogatza Plutonic Belt (Fig. 2). Swarms of northeast-trending pulaskite dikes cut the complex (Miller et al., 1976). Concentrations of allanite occur locally within and marginal to the dike swarms. Mineralization contains up to 2 percent total REE, mostly as light REE in allanite; consequently, the La+Ce/Y ratios exceed 30. Marine placer sand along Golovin Bay beaches and offshore contains abundant zircon with elevated Ta and REE (unpublished data by first author).

**Other sites in the Hogatza Plutonic Belt**

Alluvial placer gold mines have regularly recovered substantial uranothorianite, gummite and thorite in the Peace River region, the Granite Mountain intrusive complex area to the south and Utopia Creek draining Indian Mountain on the east (West, 1952). These areas are extensively covered and no bedrock sources have been reported.

The Darby Mountains Cretaceous-age granitic complex adjoins the Kachaulic pluton. It is not considered part of the Hogatza Plutonic Belt, but was found to contain numerous vein and replacement-type uranium occurrences.
(Foley and Barker, 1991). Potentially, REE may be present in these prospects but no data are available.

Ruby terrane

In central Alaska, a major northeast-trending Cretaceous batholith complex — spanning 99 to 113 Ma — is aligned with the northwest side of the Kaltag-Porcupine Fault. This batholith complex comprises several dozen mapped plutons of multi-phased biotite granite and quartz monzonite. The batholith extends for about 400 km (248 miles) from the Kokrine Hills-Melozitna region (#11, Fig. 5) on the southwest to the Chandalar River region on the northeast. Available rock chemistry indicates these rocks are peraluminous (Al>Na+K+Mg) and K- and SiO₂-rich (68-76 percent SiO₂) S-Type granites comparable to the operator (Barker and Warner, 1985). The source 270-t (300-st) Sn resource was reported by the operator (Barker, 1991b, 1991c). Mineralogical study of panned concentrates from the Ruby Terrane indicated gangue of primarily ilmenite with cassiterite, zircon, wolframite (ferberite end-member), monazite with lesser xenotime and trace amounts of scheelite and yttrofluorite. Panned concentrates contain up to 50 percent Sn, and up to 5 percent each of TREE and W. Nb averages about 0.4 percent in the concentrates. Limited assay data suggest a La+Ce/Y ratio of about 3.7, indicating a presence of HREE. The North of the Hot Springs pluton (#5), scheelite becomes more abundant in the heavy minerals. Several prospects containing scheelite skarns are known (Clautice, 1983).

An unconventional type of REE occurrence is found in Tertiary-age coal seams within a semi-closed basin along the Ray River (Barker, 2006). Calcium-rich, high-sulfur (>1.4 percent S) coal ash contains up to 1 percent each of W, Ge and Pb, along with lesser levels of REE, Au, Ga and U, as compared to unmineralized ash with 0.2 percent S or less in the neighboring basins. The total REE values in ash are 0.1-0.2 percent with a La+Ce/Y ratio of 0.92 (incomplete data set). Microprobe analyses indicate the coal formed in peat beds that were likely saturated by geothermal water concurrent with rifting of the Ruby terrane and covered by Miocene-age flood basalt flows. Nearby geothermal springs tested positive for tungsten.

Porcupine Plateau

The Porcupine Plateau is located in remote northeast Alaska (Fig. 2) within lands now designated by U.S. Congress as off limits to mineral development and managed by the U.S. Fish and Wildlife Service (http://arctic.fws.gov/ccpwsumfindings.htm). Late Devonian-age granitic rocks compose the Old Crow batholith and several smaller plutons, forming a mineral provenance that crosses the Alaska-Yukon Territory border into Canada. Several occurrences of vein-type uranium containing HREE were discovered in the Old Crow granite
in the 1970s during reconnaissance government mineral resource evaluations (Barker, 1981a; Averett and Barker, 1981; Friedman, 1982).

The Old Crow Batholith area is deeply weathered and eroded, having escaped the Pleistocene glacial advances. Alluvial stream development draining the batholith is extensive. Bulk alluvial sampling indicates extensive concentrations of Sn and REE minerals, mostly due to abundant cassiterite and monazite (Barker, 1981b).

Molybdenum and tungsten porphyry mineralization occurs at Bear Mountain, in a multi-phased porphyry deposit about 1 km (0.62 mile) in diameter (Barker and Swainbank, 1986). There is an apparent zonation transitioning from an upper zone of W-topaz capped by massive silica to a lower oxidized zone that is molybdenum-rich. A Pb-rich halo surrounds the complex. REE is believed to be associated with the high-grade (>0.2% W) core zone, but little REE data are available (Averett and Barker, 1981).

Southwest flank of the Alaska Range

Alkaline and peralkaline intrusions occur along the west flank of the Alaska Range, about 250 km (155 miles) west of Anchorage. The area includes the headwaters of the Middle Fork, Windy Fork and Swift rivers, all tributaries to the Kuskokwim River (Fig. 6). The terrain is rugged and deeply carved by active or recent glaciers. Interest in the area developed when several occurrences of eudialyte (REE-bearing) mineralization in peralkaline intrusions were reported by the Alaska Division of Geological & Geophysical Surveys (Gilbert et al., 1988; Solie, 1983). Two of these occurrences analyzed at 0.4 to 1.4 percent Y\textsubscript{2}O\textsubscript{3} and 0.2 to 0.3 percent Ce\textsubscript{2}O\textsubscript{3}. Additionally, a large alluvial fan deposit has accumulated below the Windy Fork peralkaline granite. In decreasing order of abundance, the heavy minerals include ilmenite, magnetite, zircon, chevkinite, allanite, monazite, kainosite and thorite (unpublished data by first author). A similar outwash of heavy minerals occurs below a blue feldspathic stock on the upper Swift River (unpublished data by authors).

In 2009, claims were located in the area by Hinterland Metals Inc. (Szumigala et al., 2010).

Isolated occurrences in interior Alaska

Lime Peak. Several isolated occurrences of REE are found in the Interior region. Tin occurrences are associated with greisen veins in the Lime Peak area and near Ketchum Dome plutons, which each commonly contain accessory monazite (Burton et al., 1985). Monazite and cassiterite occur locally in alluvial gravels, but their concentrations are too low and the sediments are too limited for these to be considered an REE resource. No elevated REE assays were found from the greisen veins.

Tofty. Approximately 75 km (46 miles) west of Fairbanks, near the Tofty Sn-Au placer mining camp, carbonatite dikes about 30-m (98-ft) thick can be traced along strike for up to 20 km (12 miles) (Southworth, 1984; Reifenstuhl et al., 1998). Low levels of Nb and LREE are present in aegirine, euxenite, monazite and columbite. These minerals are somewhat enhanced in the oxidized regolith. Sampling found less than 1 percent Ce +La with only trace Y and about 0.07 percent Nb. Disseminated magnetite in the carbonatite allows the dikes to be traced under surficial cover. No alkaline rocks are known to occur in the area.

Roy Creek. Vein prospects in the White Mountains are hosted by a small Cretaceous body of syenite and nepheline syenite. At least two occurrences of highly mineralized, structurally controlled REE-Th-U-rich zones are known (Burton, 1981; Armbrustmacher, 1989). The
A syenite body is the only known alkaline body in the region. Anomalous U and Th are common in stream sediments of the region to the east (Barker and Clautice, 1977).

In 1979, a 35-cm-(14-in.)-long channel sample from the P-pit exposure contained 19.3 percent TREE, including 0.25 percent Dy and 0.05 percent Tb (unpublished data by authors). The La+Ce/Y ratio was 8.43. The channel sample also contained 9.8 percent Th and 0.61 percent U. Major mineralogy was britholite, thorianite and uraninite, with minor allanite, xenotime, bastnäesite, Nd-phosphate, parisite, synchysite and thorite (written communications, R. Grauch, 1983, and A. Mariano, 9-29-2010).

Sleitat. The Sleitat deposit, located in southwest Alaska, could host an inferred tin-tungsten deposit with resource potential of 58 to 96 million kg (128 to 212 million lbs) of Sn in a 26-Mt (28.6-million st) deposit with a grade of 0.37 percent Sn and 0.04 percent W (Burleigh, 1991). Recent work by Tripp et al. (2009) reported the widespread occurrence of ‘dark’ Eu-rich monazite in the vicinity of Sleitat Mountain and hills north into the Taylor Quadrangle. Dark monazite is generally characterized by lower contents of U-Th than normal yellow monazite. The source is believed to be sericite schist.

Seward Peninsula
Lost River. Tin granites in the western Seward Peninsula are well-known, and historic alluvial and lode mining for tin has occurred. Tin occurs in skarns, but greisen zones constitute the larger known resources with a potential presence of REE. However, few if any REE analyses have been conducted. At the Lost River Mine, a mineralized greisen, intrusion breccia and peripheral skarn were mined for Sn; each contains abundant fluorite (Dobson, 1982; Hudson and Arth, 1983). Also, at the Kougarok prospect, a zinnwaldite-rich, Cretaceous tin-bearing topaz-tourmaline greisen sill and greisenized granite pipes reportedly contain minor Ta and Nb with a significant Sn resource (Puchner, 1986).

Cape Wales. In the Bering Strait, north-flowing currents transport sediment through the strait, which is deposited on the Cape Prince of Wales shoal to the northeast of the Straits and periodically reworked by storm events (Barker, 1990b). Resulting transport is to the east, with deposition creating barrier islands along the Seward Peninsula northern coast. Further transport along the coast occurs by aeolian processes. Heavy-mineral sorting concentrates heavy minerals in offshore sands (Fig. 7) that can contain up to 8 percent heavy mineral content, occurring in shallow water between the shoal and the beach. Concentrates from bottom sediment cores contained ilmenite, zircon, magnetite, monazite, chromite, xenotime and wolframite; most samples reported trace gold values.

Juneau area
William Henry Bay. A syenite body is cut by thin, radioactive dikes composed of carbonatite and trachyte. In the 1950s, a drill hole tested the zone at depth and reported that 0.022 percent U was found. Low Nb and REE values were reported in surface samples (Warner, 1985).
Apparent karst topography in the area may indicate carbonate leaching, but no bedrock outcrop was available.

**Kook Lake.** Farther south, southeast of Teneeke Springs and near Kook Lake (Fig. 2), is a syenite and nepheline syenite body, which is part of the Sitkoh alkalic plutonic suite (Ford et al., 1990). A high radiometric background occurs over narrow zones within the syenite and soil overburden, but only low REE and Nb values were detected (Barker and Lamal, 1988). Analysis of a 25-kg (55-lb) bulk sample of the best mineralized zone reported 1.4 percent TREE predominated by LREE and a La+Ce/Y ratio of 60.

**Black Crag.** Government surveys reported elevated REE and Y in rock samples from an occurrence of molybdenum porphyry northeast of Wrangell (Fig. 2), but no other data are available (Still, et al., 2002).

**Prince of Wales Island**

**Dora Bay.** Pegmatite dikes, vein-dikes, silica-rich veins and disseminated eudialyte, all containing REE, are associated with an intrusive complex of peralkaline granite, syenite and nepheline syenite (Fig. 8) along the peninsula between Dora Lakes and the South Arm of Chalmondeley Sound (Eberlein et al., 1983; Barker and Mardock, 1990). Coarse-grained pegmatite dikes, evolved from late stage fractionation of the intrusion, progressively grade into the vein-dikes and ultimately into the silica-rich veins. The percentages of REE and SiO$_2$ increase proportionately through this transition. Dike and vein structures are narrow, ranging from 10 cm to 1 m (4 in. to 3 ft) in thickness, but they can be traced for 3 km (1.8 miles) along an apparent north-south fracture zone. Geochemical analyses indicate increasing concentrations of incompatible HFSE at increasing distance from the peralkaline complex. The area is heavily forested and bedrock exposures are limited. The REE mineralogy exhibits fine-grained intergrowths of principally thalenite and bastnäesite, with lesser monazite and eudialyte. Euxenite hosts most of the Nb values.

An estimate of resource potential in the district ranges from 1.5 to 7.7 Mt (1.7 to 8.5 million st) at an average grade of 0.5 percent TREE+Y, of which 50 percent is HREE (Barker and Mardock, 1990). Three bulk samples from near Dora Lakes composed of the principal vein-dike and vein locations reported an average La+Ce/Y ratio of 1.32. Mineralization also occurs as disseminated eudialyte in syenite near the head of Dora Bay, but its extent is unknown. In 1998, Philpotts et al. reported REE and Y values along with molybdenite occurring in recently opened rock quarry exposures in the west center of the map area. A creek valley 1 km (0.62 miles) west of Dora Lakes contains anomalous Y in heavy mineral samples and mineralized vein rubble is found 2 km (1.2 miles) west of Dora Lakes on the South Arm, which suggests that additional dike systems lie in the intervening highland. The Dora Bay area mineral rights are privately held by the SeaAlaska Corporation.

**Salmon Bay.** Located on northern Prince of Wales Island (Fig. 2), the Salmon Bay occurrence comprises at least 70 radioactive carbonate veins with widths of <1 cm to 3 m (0.4 in. to 10 ft) and individually up to 300 m (984 ft) in length. The prospect has been described by Houston (1952), Houston et al., (1955) and Warner (1989). Mineralogical studies indicate the chief radioactive mineral is thorite, associated with monazite, bastnäesite, parasite and columbite in a matrix of ankerite, dolomite, siderite, quartz and albite. Numerous lamprophyre dikes occur that are subparallel to the carbonate dikes. Sampling indicated a resource potential of about 680 kt (750,000 st) containing very low REE (primarily LREE) and Nb values (Warner, 1989).

**Stonerock Bay.** A large mass of monzonite, quartz monzonite, syenite and lesser amounts of pyroxenite occur south of McLean Arm and extend south to Nichols Bay (Fig. 2). Reconnaissance mapping was completed by Gehrels (1992), who suggested a Silurian age for the intrusive rock complex. Within the monzonite and bordered by pyroxenite are meter-sized mineralized pods.
and stockwork lenses that grade to breccias and veins of radioactive carbonatite; they are exposed at beach level between Stonerock and Mallard Bays. Samples contain up to 2 percent TREE as mostly LREE; the La+Ce/Y ratio is 37. No REE mineralization has yet been found inland, where forest and ground vegetation matte is extensive.

**Discussion**

Currently, the only advanced REE project in Alaska is the Bokan Mountain property operated by Ucore Rare Metals in the southern part of Prince of Wales Island. Elsewhere in Alaska, encouraging and intriguing prospects for REE deposits occur in several favorable geologic terranes. The most promising prospects are those with available geological and geochemical data; enrichments in the highly desired HREE; favorable land classifications and political factors; and realistic access to the location. Based on these factors, the authors suggest that the most promising REE-bearing deposits are the Bokan Mountain and Dora Bay deposits hosted by peralkaline rocks in southeast Alaska, and the alluvial deposits of the many rivers and streams that drain the Ruby Terrane. Should access to the Kobuk Ambler copper deposits in northwest Alaska be developed in the future (western Alaska access under present study by state of Alaska), then some of the occurrences in the Hogatza plutonic belt may also become significant targets for exploration.

Most of the Alaska REE occurrences are vein-type, poly-mineral prospects, related to alkaline and peralkaline complexes, or alluvial deposits that contain monazite (\( \text{CePO}_4 \)) and xenotime (\( \text{YPO}_4 \)) with coproducts of cassiterite, wolframite, zircon and, locally, gold. No large carbonatites have been identified in Alaska, although several prospects — such as Tofty and Salmon Bay — contain carbonatite dikes that are variably radioactive and exhibit at least low-grade REE-Nb-Th values. These carbonatite dikes do not appear to warrant further investigation at this time.

Several of the REE occurrences within Alaska provide evidence that those prospects associated with the most advanced hydrothermal alteration are also those that likewise contain increased proportions of HREE relative to the LREE. Examples include: silica-rich veins at Dora Bay (Fig. 9); several Bokan Mountain prospects (Piper, Wennie, Ross Adams and others; Fig. 10); xenotime in placers associated with Sn-greisens in the Ruby Terrane; and vein-dikes at the Zane Hills in the Hogatza belt. All these examples have increased HREE to LREE ratios; within some deposits HREE comprise more than 90 percent of the contained TREE. Hydrothermal enrichment of REE and HFSE in highly fractionated alkaline and peralkaline complexes has been reported elsewhere (Silvi and William-Jones, 2005), but the percentage of HREE to TREE has not been specifically reported. The examples in Alaska suggest that hydrothermal enhancement of rare earths is not only likely, but in some cases the enrichment is additionally biased towards the HREE.

As exploration advances at Bokan Mountain, it appears likely the operator will continue to add additional and substantial REE resources to the initial inferred estimate, which was based on drilling completed in 2007-2010 (http://ucore.com). The Bokan Mountain resources contain an average of about 40 percent HREE + Y. Thus, if mining of these deposits is found possible, this district could provide some of the Dy and Tb, which is predicted to become in critical short supply. With other prospects on the Bokan property largely untested, it is possible the REE resource at Bokan Mountain may eventually meet or even exceed the government’s 1989 estimate of 177 kt (195,000 st) of REE+Y (Warner and Barker, 1989).

Thus far, only one REE project in Alaska — Bokan Mountain — has reached an advanced stage of exploration. However, the numerous alkaline intrusive complexes in Alaska, combined with the tantalizing results of a number of past reconnaissance studies, suggest that more REE potential exists in Alaska. Many of the REE prospects lie in remote regions, but that has never dissuaded the hardy Alaskan prospectors of the past. (Any use of trade, product or firm names is for descriptive purposes only and does not imply endorsement from the U.S. government.)

(References available from the authors.)