Thematic Article

Rare Earth Deposits of North America

Stephen B. Castor

Nevada Bureau of Mines and Geology, University of Nevada, Reno, Nevada, USA

Abstract

Rare earth elements (REE) have been mined in North America since 1885, when placer monazite was produced in the southeast USA. Since the 1960s, however, most North American REE have come from a carbonatite deposit at Mountain Pass, California, and most of the world's REE came from this source between 1965 and 1995. After 1998, Mountain Pass REE sales declined substantially due to competition from China and to environmental constraints. REE are presently not mined at Mountain Pass, and shipments were made from stockpiles in recent years. Chevron Mining, however, restarted extraction of selected REE at Mountain Pass in 2007. In 1987, Mountain Pass reserves were calculated at 29 Mt of ore with 8.9% rare earth oxide based on a 5% cut-off grade. Current reserves are in excess of 20 Mt at similar grade. The ore mineral is bastnasite, and the ore has high light REE/heavy REE (LREE/HREE). The carbonatite is a moderately dipping, tabular 1.4-Ga intrusive body associated with ultrapotassic alkaline plutons of similar age. The chemistry and ultrapotassic alkaline association of the Mountain Pass deposit suggest a different source than that of most other carbonatites. Elsewhere in the western USA, carbonatites have been proposed as possible REE sources. Large but low-grade LREE resources are in carbonatite in Colorado and Wyoming. Carbonatite complexes in Canada contain only minor REE resources. Other types of hard-rock REE deposits in the USA include small iron-REE deposits in Missouri and New York, and vein deposits in Idaho. Phosphorite and fluorite deposits in the USA also contain minor REE resources. The most recently discovered REE deposit in North America is the Hoidas Lake vein deposit, Saskatchewan, a small but incompletely evaluated resource. Neogene North American placer monazite resources, both marine and continental, are small or in environmentally sensitive areas, and thus unlikely to be mined. Paleoplacer deposits also contain minor resources. Possible future uranium mining of Precambrian conglomerates in the Elliott Lake–Blind River district, Canada, could yield by-product HREE and Y. REE deposits occur in peralkaline syenitic and granitic rocks in several places in North America. These deposits are typically enriched in HREE, Y, and Zr. Some also have associated Be, Nb, and Ta. The largest such deposits are at Thor Lake and Strange Lake in Canada. A eudialyte syenite deposit at Pajarito Mountain in New Mexico is also probably large, but of lower grade. Similar deposits occur at Kipawa Lake and Lackner Lake in Canada. Future uses of some REE commodities are expected to increase, and growth is likely for REE in new technologies. World reserves, however, are probably sufficient to meet international demand for most REE commodities well into the 21st century. Recent experience shows that Chinese producers are capable of large amounts of REE production, keeping prices low. Most refined REE prices are now at approximately 50% of the 1980s price levels, but there has been recent upward price movement for some REE compounds following Chinese restriction of exports. Because of its grade, size, and relatively simple metallurgy, the Mountain Pass deposit remains North America's best source of LREE. The future of REE production at Mountain Pass is mostly dependent on REE price levels and on domestic REE marketing potential. The development of new REE deposits in North America is unlikely in the near future. Undeveloped deposits with the most potential

are probably large, low-grade deposits in peralkaline igneous rocks. Competition with established Chinese HREE and Y sources and a developing Australian deposit will be a factor.

1. History of production of rare earth elements in North America

During the late 1800s and early to mid 1900s, North American rare earth elements (REE) came mainly from placer deposits. Approximately 5000 t of monazite were produced between 1885 and 1917 from the Carolina monazite belt, and REE minerals were produced in the 1950s from placers in Idaho where dredging operations near the town of Cascade and in Bear Valley produced approximately 7000 t of monazite, and an unknown amount of monazite and euxenite, respectively, on the basis of data from Overstreet (1967) and Kline *et al.* (1953). Between 1952 and 1994, by-product REE were recovered from mineral sands at Green Cove Springs, Florida. Metamorphosed Early Proterozoic conglomerate mined for uranium at Blind River, Ontario, Canada, was the source of minor REE production from the 1950s to 1970s, and again from 1986 to 1990. In the 1950s a small amount of bastnasite was produced from a fluorite deposit in the Gallinas Mountains, New Mexico (Adams, 1965).

Between 1965 and 1995 most of the world's REE came from the Mountain Pass, California, bastnasite deposit. The Mountain Pass operation of Molycorp (now part of Chevron Mining Inc.) produced rare earths since 1954, and from the 1960s to the mid 1990s was the world's largest source of rare earth commodities. After 1998, Mountain Pass rare earth sales declined substantially due to competition from China and to environmental constraints. The rare earth separation plant at Mountain Pass was shut down in 1998 (Hedrick, 1999) and mining ceased during 2002 (Hedrick, 2003). In recent years the operation was in care-and-maintenance status and shipments were made from stockpiles (Hedrick, 2007). In 2007, however, Chevron Mining restarted part of the REE extraction plant in order to produce commodities containing La, Nd, and Pr.

2. Geology of North American REE deposits

2.1. Carbonatite deposits

Many carbonatite intrusions are enriched in REE; Orris and Grauch (2002) list more than 100 carbonatite occurrences that contain REE minerals. Brief descriptions of REE mineral occurrences in carbonatites worldwide may be found in Mariano (1989), Woolley (1987), and Wall and Mariano (1996). Productive REE deposits and potential REE resources in North America are dominated by carbonatite deposits (Table 1). Despite the abundance of REE-bearing carbonatites, REE have been produced from only one such deposit in North America, the Mountain Pass deposit in California (Fig. 1).

The Mountain Pass deposit was mined exclusively for REE beginning in 1954 by Molycorp (originally Molybdenum Corporation of America). In 1987, proven and probable reserves were calculated at 29 Mt with an average grade of 8.9% rare earth oxide (REO) based on a 5% cut-off grade (Castor, 1991). Current reserves are in excess of 20 Mt of ore at similar grade (Castor & Nason, 2004). The ore typically contains 10–15% bastnasite, 65% calcite and (or) dolomite, and 20–25% barite. Other gangue minerals, such as strontianite and talc, are present in significant amounts locally. Galena is locally abundant but other sulfide minerals are rare. Bastnasite is the mineral processed, although nine other REE minerals occur at Mountain Pass (Castor & Nason, 2004). Mountain Pass bastnasite has high light REE/heavy REE (LREE/HREE; Table 2). The major oxide chemistry of Mountain Pass REE ore types is shown in Table 3.

The Mountain Pass carbonatite, which has been dated at approximately 1.4×10^9 years (DeWitt *et al.*, 1987), is a moderately dipping, tabular intrusion (Fig. 2) into granulite grade gneiss. It is associated with ultrapotassic alkaline plutons of similar age, size and orientation, as well as with abundant carbonatite and alkaline dikes, and is in a narrow north-trending zone of ultrapotassic alkaline igneous rocks at least 130 km long (Castor, 1991; Castor & Nason, 2004).

The Mountain Pass deposit shares features with other carbonatites in the world. It has textural and structural features that support igneous intrusive origin (Olson *et al.*, 1954); it has associated alkali-rich fenitic alteration; and its chemistry is broadly indicative of carbonatite origin. However, the shape of the carbonatite orebody, its ultrapotassic alkaline association (most carbonatites are associated with alkaline rocks that are dominantly sodic), and some details of its chemistry (it is unusually low in iron and phosphorus for REE-rich carbonatite), suggest that its source was different than that of most other carbonatites (Castor &

Table 1 Size and grade of some productive and potentially productive North American rare earth deposits

Name	Country	State/Province	REO (Mt)	REO %	Source	Comments
Carbonalite						
Iron Hill	USA	Colorado	2.600	0.42	Jackson and Christiansen (1993)	By-product of Nb
Mountain Pass	USA	California	1.800	8.9	Castor and Nason (2004)	5% REO cut-off
Bear Lodge	USA	Wyoming	0.380	3.3	Meyer (2002)	Carbonatite dikes
Oka	Canada	Quebec	0.221	0.1	Orris and Grauch (2002)	By-product of Nb
Wet Mountains	USA	Colorado	0.140	1.0	Orris and Grauch (2002)	Dike deposits, high Th
Hicks Dome	USA	Illinois	0.062	0.42	Jackson and Christiansen (1993)	By-product of Nb
Alkaline rock						
Thor Lake	Canada	NW Territories	1.547	0.41	Orris and Grauch (2002)	
Strange Lake	Canada	Labrador–Quebec	0.440	0.85	Richardson and Birkett (1996)	
Lackner Lake	Canada	Ontario	0.130	2.72	Orris and Grauch (2002)	
Pajarito Mountain	USA	New Mexico	0.004	0.18	Jackson and Christiansen (1993)	REO = Y_2O_3 only
Kipawa Lake	Canada	Quebec	ND	≥0.10	Richardson and Birkett (1996)	REO = Y_2O_3 only
Iron oxide-REE						
Mineville	USA	New York	0.160	1.04	Jackson and Christiansen (1993)	Apatite in mill tails
Pea Ridge	USA	Missouri	0.072	12.0	Orris and Grauch (2002)	
Vein						
Powderhorn	USA	Colorado	0.886	0.36	Jackson and Christiansen (1993)	Stockwork veins
Lemhi Pass	USA	Idaho	0.199	0.51	Jackson and Christiansen (1993)	
Hoidas Lake	Canada	Saskatchewan	0.035	2.56	Great Western Minerals Group (2007)	Allanite and apatite
Diamond Creek	USA	Idaho	0.003	1.22	Jackson and Christiansen (1993)	
Placer						
Oak Grove	USA	Tennessee	0.157	0.09	Jackson and Christiansen (1993)	Monazite
Idaho placers	USA	Idaho	0.150	0.01	Jackson and Christiansen (1993)	Mostly monazite
Hilton Head Island	USA	South Carolina	0.061	0.01	Jackson and Christiansen (1993)	Monazite
Carolina placers	USA	N. and S. Carolina	0.057	ND	Jackson and Christiansen (1993)	Monazite
Cumberland Island	USA	Georgia	0.027	0.01	Jackson and Christiansen (1993)	Monazite
Green Cove Spring	USA	Florida	0.005	0.005	Jackson and Christiansen (1993)	Monazite
Paleoplacer						
Elliott Lake	Canada	Ontario	0.020	0.009	Jackson and Christiansen (1993)	Monazite
Bald Mountain	USA	Wyoming	0.014	0.12	Jackson and Christiansen (1993)	Monazite
Phosphorite						
Idaho deposits	USA	Idaho	0.100	0.1	Jackson and Christiansen (1993)	Several deposits
Fluorite						
Gallinas Mountains	USA	New Mexico	0.001	2.95	Orris and Grauch (2002)	

ND, no data; REE, rare earth element; REO, rare earth oxide.

Nason, 2004). The chemistry of the ultrapotassic alkaline rocks at Mountain Pass suggests that they were derived from primitive or depleted mantle mixed with an enriched mantle or crustal component, and the carbonatite likely came from a similar source. The Mountain Pass LREE deposit occurs in a northeasterly trending belt of anorogenic Middle Proterozoic plutonism that crosses the North American continent (Anderson, 1983) and contains eight Middle–Late Proterozoic REE deposits (Castor, 1993, 1994).

Although there are mineral and chemical similarities between the Mountain Pass and the huge Bayan Obo deposits in China, there are also some major differences. Like the Bayan Obo ore, the Mountain Pass carbonatite ore has extreme LREE enrichment with no europium anomalies (Fig. 3) and low $^{87}Sr/^{86}Sr$. As at Bayan Obo, alkali-rich alteration is associated with the Mountain Pass carbonatite; in both areas alteration assemblages include sodic amphibole and potash feldspar (Olson *et al.*, 1954; Drew *et al.*, 1990). The Bayan Obo and Mountain Pass deposits are both enriched in barium and fluorine (Wu *et al.*, 1996; Castor & Nason, 2004). Samples of Bayan Obo ore, however, have an average BaO content of approximately 2.4%, and a maximum barium content of 7.7% (based on data from Chao *et al.*, 1997), much lower than Mountain Pass ore (Table 3). The fluorine content of Bayan Obo ore, which averages more than 9%, is much higher than that of Mountain
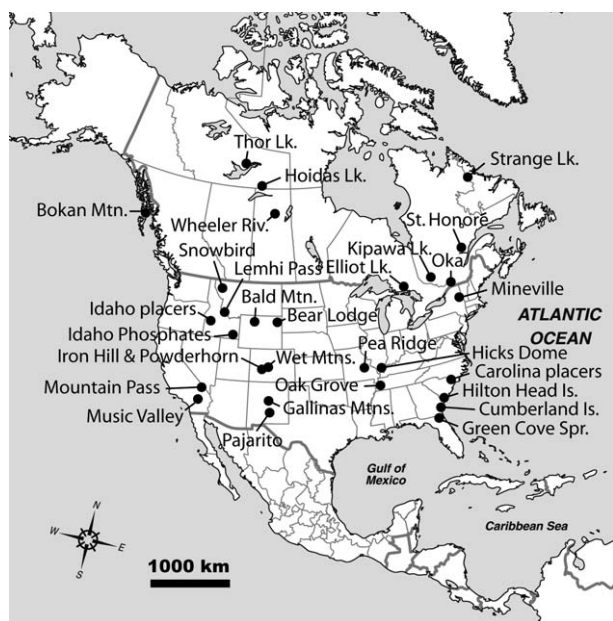
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Fig. 1 Locations of North American rare earth element deposits.

Pass ore, and Bayan Obo ore also has higher phosphorus and niobium contents. REE deposits at Bayan Obo are clearly different from Mountain Pass in their association with large amounts of iron. Whereas Mountain Pass ore contains approximately 10-fold as much bastnasite as monazite, the Bayan Obo deposits reportedly

contain approximately equal amounts of bastnasite and monazite (Qiu, Y., pers. commun., 1984), although bastnasite-rich ore is selectively mined. REE/chondrite patterns for Bayan Obo show enrichment in HREE relative to Mountain Pass (Fig. 3). Finally, the ultrapotassic alkaline intrusions that are associated with the Mountain Pass carbonatite are not found at Bayan Obo. On the basis of its relatively high P, Fe, and Nb contents, if the Bayan Obo deposit has a carbonatite-related origin, it is probably related to a nephelinite–carbonatite system, rather than to an ultrapotassic–carbonatite system as at Mountain Pass.

Elsewhere in the western USA, carbonatites have been investigated as possible sources of REE, but none rival the Mountain Pass deposit as a REE resource. Similar to the Mountain Pass carbonatite, most have high LREE/HREE. The Cambrian Iron Hill carbonatite in Colorado has been considered a possible source of REE. It contains a very large REE resource (Table 1), but its grade is only approximately 0.4–0.5% REO (Armbrustmacher, 1980; Jackson & Christiansen, 1993). Carbonatite dikes in the Powderhorn district that contain up to 3% REO constitute a resource of unknown size (Olson & Hedlund, 1981), and dikes in the nearby Wet Mountains constitute a small resource with a grade of approximately 1.1% REO (Orris & Grauch, 2002). An LREE deposit consisting of three or more parallel Tertiary carbonatite dikes in the Bear Lodge district of Wyoming contains a moderately large resource at

Table 2 REO analyses of North American REE concentrates and ores (normalized to approx. 100 wt% REO + Y_2O_3)

Oxide	Bear Lodge bulk ore	Mountain Pass bastnasite	Green Cove Spring monazite	Mineville apatite	Thor Lake xenotime	Strange Lake bulk ore
La	30.37	33.79	17.5	15.75	0.1	4.58
Ce	45.50	49.59	43.7	31.12	0.02	11.95
Pr	4.65	4.12	5.0	3.62	0.1	1.36
Nd	15.82	11.16	17.5	15.46	0.2	4.26
Sm	1.83	0.85	4.9	2.94	1.8	2.07
Eu	0.35	0.105	0.16	0.39	0.7	0.15
Gd	0.74	0.21	6.6	3.52	11.6	2.45
Tb	0.05	0.016	0.26	1.86	2.5	0.33
Dy	0.16	0.034	0.9	1.86	15.6	8.24
Ho	0.02	0.004	0.11	0.59	3.1	1.70
Er	0.03	0.006	TR	1.66	5.41	4.90
Tm	<0.01	0.002	TR	0.49	0.6	0.69
Yb	0.49	0.002	0.21	1.66	2.2	4.02
Lu	<0.01	ND	TR	0.59	0.7	0.42
Y	<0.01	0.13	3.2	18.49	55.31	52.78
Total	100.01	100.00	100.04	100.00	99.94	99.90

Data sources: Bear Lodge, Rare Element Resources (2005); Mountain Pass, Castor (1986); Green Cove Spring, Hedrick (2003); Mineville, Roeder *et al.* (1987); Thor Lake, Avalon Ventures (2007); Strange Lake, J. W. Keim, unpubl. data (1983). ND, no data; REE, rare earth element; REO, rare earth oxide; TR, trace.

Table 3 Major oxide chemistry of carbonatite samples from Mountain Pass (adapted from Castor & Nason, 2004)

Sample no.	Bastnasite-barite sovite			Silicified bastnasite-barite sovite		Talc-rich bastnasite-barite sovite		Bastnasite-barite beforsite		Bastnasite-barite dolosovite			Monazite carbonatite		
													Beforsite	Dolosovite	Breccia
	85-4†	HP 20B†	Q-648	Q-654A	R-772	Q-646	R-735	R-724†	O-822	O-833	R-711	R-744	R-757	R-733	84-6-30
SiO_2	0.40	7.09	12.20	24.60	47.50	13.70	13.50	1.63	2.20	14.10	1.30	1.50	0.50	1.40	30.50
Al_2O_3	0.01	1.29	0.06	0.05	0.16	0.08	0.03	0.01	0.17	0.08	0.02	0.04	0.02	0.03	6.40
Fe_2O_3	0.24	4.71	0.25	1.30	2.70	2.70	3.20	1.77	1.80	2.40	1.60	4.30	6.60	2.20	8.60
MgO	0.04	0.86	0.22	2.40	0.82	2.80	2.50	6.41	4.70	2.40	1.20	5.30	14.60	8.10	6.60
CaO	21.30	38.04	33.70	9.10	2.40	21.00	17.00	11.73	10.40	22.20	12.70	21.40	26.80	20.10	17.70
Na_2O	0.05	0.06	ND	ND	ND	ND	ND	0.07	ND	ND	ND	ND	ND	ND	ND
K_2O	0.05	0.85	ND	ND	ND	ND	ND	0.09	ND	ND	ND	ND	ND	ND	ND
MnO	0.24	0.18	0.30	0.08	0.41	0.41	0.50	0.45	0.46	0.51	0.38	0.83	1.40	0.52	0.22
TiO_2	0.01	0.10	ND	ND	ND	ND	ND	0.01	ND	ND	ND	ND	ND	ND	ND
P_2O_5	0.04	0.10	0.30	0.26	0.12	1.40	0.48	0.29	0.18	0.30	0.57	0.58	0.34	1.70	1.30
BaO	14.63	5.85	10.00	13.80	17.70	8.80	16.30	25.12	33.10	10.00	22.80	15.10	1.70	19.70	2.40
SrO	14.15	0.14	2.20	13.20	1.40	0.36	5.50	2.49	2.10	7.00	12.00	5.40	2.10	4.70	0.47
CO_2	19.84	21.43	29.70	18.30	5.20	20.90	17.60	18.26	16.90	25.80	20.60	27.20	43.80	25.90	16.90
SO_3	18.26	2.55	3.70	5.50	8.20	4.50	9.30	15.43	17.00	4.10	11.50	8.30	0.80	11.60	1.40
F	0.70	ND	ND	ND	ND	ND	ND	1.40	ND	ND	ND	ND	ND	ND	ND
PbO	ND	ND	0.11	0.25	0.29	0.04	1.64	ND	0.01	0.71	0.39	0.02	0.05	0.64	0.02
RE_2O_3	9.89	3.73	3.77	4.94	8.44	13.05	5.45	13.18	6.72	6.51	8.86	6.85	1.24	2.48	1.40
Total	99.85	86.97	96.51	93.78	95.34	89.74	93.00	98.34	95.74	96.11	93.92	96.82	99.95	99.07	93.91

†Major oxides by inductively coupled plasma–mass spectroscopy (ICP-ES) at Acme Laboratory, Vancouver, BC, Canada; F by colorimetry, Nevada Bureau of Mines and Geology Laboratory. Other samples: major oxides by ICP-ES (except SiO_2 and PbO) at Skyline Laboratories, Tucson, AZ, USA; SiO_2 by gravimetry, PbO by atomic absorption spectroscopy at same lab; RE_2O_3 by X-ray fluorescence spectroscopy from Molycorp, Mountain Pass. Total Fe as Fe_2O_3, ND, no data.
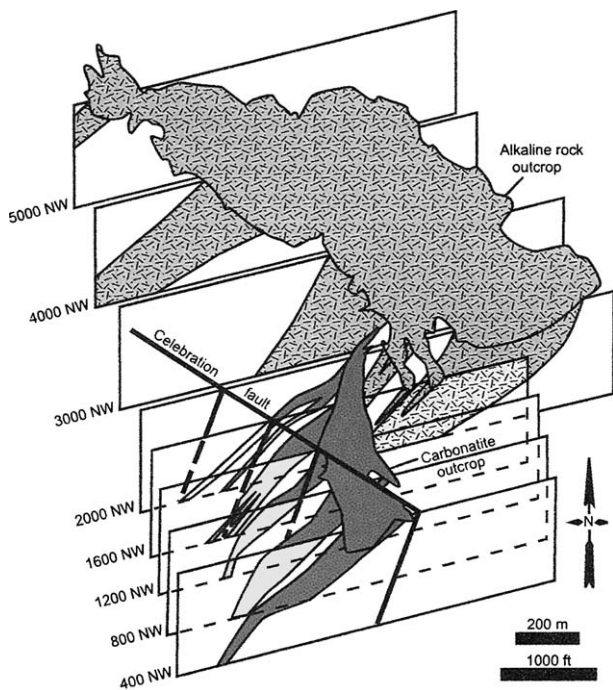
Fig. 2 Stacked cross-sections through the Mountain Pass rare earth element carbonatite orebody (gray) and a large, adjacent mass of alkaline rock (patterned). From Castor and Nason (2004).
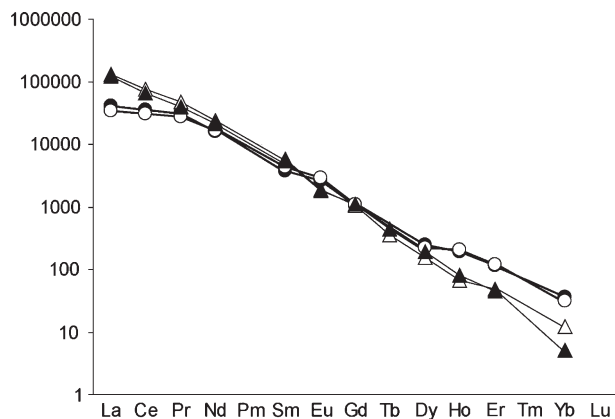

Fig. 3 Chondrite-normalized plot of rare earth elements (REE) in ores from Bayan Obo, China, and Mountain Pass, USA. (○) Bayan Obo Fe-REE-aegerine ore; (●) Bayan Obo Fe-REE-fluorite ore; data from Yuan *et al.* (1992). (△) Mountain Pass beforsite ore; (▲) Mountain pass sovite ore; data from Castor (1986). REE data not normalized to 100% prior to chondrite normalization.

approximately 3.3% REO with ancylite as the ore mineral (Meyer, 2002). A late Paleozoic Nb carbonatite resource at Hicks Dome in Illinois includes a relatively small REE resource.

Carbonatite complexes in eastern Canada also contain REE mineralization. A Mesozoic Nb carbonatite at Oka, Quebec contains a moderate-sized REE resource (Orris & Grauch, 2002). Bastnasite and monazite zones containing up to 4.5% LREE have been identified in the Late Proterozoic St-Honore complex in Quebec, with one 80-m drill intercept averaging >3% REO (Vallee & Dubuc, 1970).

2.2. HREE deposits in peralkaline igneous rocks

Many REE deposits occur in peralkaline igneous rocks and resources can be large, but most such deposits are relatively low grade, and only a single deposit in Russia has been mined. Peralkaline REE deposits are typically enriched in yttrium, HREE, and zirconium. Future development of such deposits is probably dependent on the market for zirconium.

During the 1980s, when yttrium demand exceeded supply, exploration in North America for yttrium-rich REE deposits led to the discovery of zirconium and HREE-dominated resources that are associated with peralkaline syenitic and granitic rocks. Some have associated Be, Nb, and Ta. Some of these resources are large, but have low REE contents compared with commercial LREE-dominated deposits (Table 1). Richardson and Birkett (1996) give an overview of Canadian peralkaline rock-associated deposits, and compare them with similar deposits worldwide.

Deposits at Thor Lake in the Northwest Territories, Canada (Trueman *et al.*, 1988; Taylor & Pollard, 1996) may constitute the largest resource of this type in North America. Orris and Grauch (2002) reported the resource at 65 Mt of ore at 1.7% REO (approx. 1.55 Mt REO). The deposits also contain high but variable Zr, Nb, and Ta contents. REE minerals include xenotime, gadolinite, monazite and REE carbonates. Recent data on two specific zones at Thor Lake indicate a drilled resource of 1.14 m tonnes at 0.71% Y_2O_3 + REO (Avalon Ventures, 2007).

The Strange Lake Zr-HREE-Nb-Be deposit in Quebec–Labrador (Fig. 1) is a potentially large resource in a circular peralkaline granite complex approximately 6 km in diameter (Currie, 1985). Orris and Grauch (2002) reported 52 Mt at 0.54% REO + 0.31 Y_2O_3, for a total

resource of approximately 0.44 Mt REO (including Y_2O_3). An earlier resource estimate was 5 Mt containing 0.5% yttrium and 3% zirconium along with beryllium, niobium, and tantalum credits (Miller, 1988). Most of the Strange Lake REE are in gadolinite, bastnasite, and kainosite (Mariano, A. N., pers. comm., 1989). Alkaline complexes in the Shallow Lake and Letitia Lake areas in Labrador, approximately 250 km southeast of Strange Lake, also include rocks with high yttrium content (Currie, 1976; Miller, 1988).

Foliated syenite at Kipawa Lake, Ontario, includes a 1300 × 100-m zone of yttrium- and zirconium-rich rock that contains eudialyte, mosandrite, and britholite (Allan, J., pers. comm, 1993). The Y_2O_3 content of this deposit is comparable to that at Pajarito Mountain, but grade varies widely within the deposit, which was intensely deformed during the Grenville orogeny.

A HREE-zirconium deposit at Pajarito Mountain in New Mexico containing 2.4 Mt of rock with 0.18% Y_2O_3 and 1.2% ZrO_2 (Sherer, 1990) consists of a 10-km^2 dome-shaped syenite intrusion (Kelley, 1968). The main zirconium-REE phase was found to be eudialyte (Mariano, 1989). Granite- and syenite-associated HREE resources with Y_2O_3 contents of approximately 0.2% have also been identified at Bokan Mountain in southeastern Alaska (Barker & Mardock, 1988).

2.3. Vein deposits

REE deposits in veins are typically small in comparison to the commercial hard rock deposits at Bayan Obo and Mountain Pass. Nevertheless, REE have been produced from two vein deposits in Africa in the past, and more recently from two such deposits in China that may actually be carbonatite dikes. Several North American REE vein deposits have been investigated but not mined.

The largest REE vein resource in North America consists of stockwork veins in alkaline rock in the Powderhorn district of Colorado (Table 1; Staatz, 1983). The grade, however, is <0.5% REO (Jackson & hristiansen, 1993).

REE- and thorium-bearing quartz veins scattered over an area of approximately 250 km^2 at Lemhi Pass on the Idaho–Montana border in the USA (Staatz et al., 1979) comprise a moderate REE resource (Table 1). The mineralization is mostly LREE dominated and averages <1% REO, but some veins contain as much as 0.3% Y_2O_3 and 2.0% total REO. A small area at Diamond Creek approximately 50 km northwest of Lemhi Pass contains veins with similar mineralogy, but with lower LREE/HREE ratios.

The most recently discovered North American REE vein deposit is at Hoidas Lake in northwestern Saskatchewan. A measured and indicated resource of 1.15 Mt at 2.83 wt% REO + Y_2O_3 has been announced (Great Western Minerals Group, 2007). The REE are in allanite- and apatite-bearing veins that may be metamorphosed equivalents of pyroxene-rich ultramafic to lamprophyric dikes (Harvey et al., 2002).

The Snowbird occurrence in northwestern Montana is a REE resource of unknown size in a Cretaceous quartz–carbonate–fluorite–parisite vein considered to be of hydrothermal origin (Metz et al., 1985). Thorite-bearing quartz–carbonate–fluorite veins at Hall Mountain near Porthill in northernmost Idaho contain as much as 0.2% Y_2O_3.

A monazite–apatite vein cuts Precambrian granite near Crescent Peak in Nevada approximately 30 km east of the Mountain Pass REE deposit (Castor, 1991). The vein is small and of little interest economically. It is interesting because its REE distribution includes a prominent negative Eu anomaly, which suggests a different origin than for the Mountain Pass carbonatite.

2.4. Iron–rare earth element deposits

The huge iron-REE deposit at Bayan Obo is the world's largest REE resource. Two relatively small iron-REE deposits in the USA may fall into this class of deposit.

Mill tailings from historic processing of magnetite deposits in Precambrian gabbro and syenite at Mineville, New York, are a REE resource of moderate size (Table 1). They contain apatite that averages >11% REO, including approximately 2% Y_2O_3 (McKeown & Klemic, 1956).

The Pea Ridge iron deposit in Missouri contains an unexploited high-grade REE resource of unknown but probably small size in breccia pipes associated with 1.48×10^9-year-old granite and syenite (Kisvarsanyi et al., 1989). Bulk samples of REE-rich breccia, which contains monazite and xenotime, average approximately 12% REE (Nuelle et al., 1992). Although the Pea Ridge resource is LREE dominated, it also contains significant HREEs.

2.5. Placer deposits

Most placer accumulations with significant amounts of REE minerals are Tertiary or Quaternary deposits derived from source areas that include granitic rocks or high-grade metamorphic rocks, but paeloplacer deposits that are as old as Precambrian contain REE resources. Orris and Grauch (2002) list more than 360

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REE-bearing placers worldwide. In the 1980s, monazite and xenotime from titania–zircon paleobeach placers in Australia were the third most important source of REE in the world, but Australia currently exports little or no REE minerals from such sources owing to its high thorium content.

Minor resources of REO are in modern marine placers in the southeastern USA, such as at Hilton Head Island in South Carolina (Table 1). The Carolina monazite belt has placer reserves that average 0.25 kg m^{-3} of monazite (Overstreet, 1967). Scattered alluvial placers in Idaho comprise a moderate sized REO resource. Jackson and Christiansen (1993) listed five separate Idaho placer deposits that together constitute a moderate-sized resource. Monazite reserves were estimated at 38,000 t in the Cascade, Idaho placers (Overstreet, 1967). Bear Valley, Idaho, contains an estimated 10,000 t of REO along with significant Nb and Ta on the basis of data from Kline *et al.* (1953). Approximately 500 t of monazite per year were produced from 1952 to 1994 as a by-product from titania–zircon production from Pleistocene marine sands near Green Cove Springs in Florida. The sands, which were mined by dredging, now constitute a minor REE resource (Table 1).

Unconsolidated Cretaceous Ti-Zr mineral sands at Oak Grove in Tennessee are probably the largest North American placer REE resource (Table 1). The deposit, which was discovered and evaluated in the 1960s, has never been mined. Metamorphosed Early Proterozoic conglomerate mined for uranium in the Elliot Lake–Blind River district, Ontario, Canada, contains REE in monazite, uraninite, and brannerite (Roscoe, 1969) and was the source of minor REE production from the 1950s to 1970s, and again from 1986 to 1990. The heavy minerals in this ore are believed to be primarily of placer origin with possible enrichment during metamorphism or hydrothermal activity. Of the approximately 230 Mt of ore averaging 0.1% U_3O_8 estimated to be present in the district in 1973 (Robertson, 1981), perhaps half remained in the early 1990s. Uranium mining ended in 1996, but mining may resume if uranium prices remain high, and HREE and Y could conceivably be produced as by-products.

At Music Valley in southern California, small xenotime- and monazite-rich zones with as much as 16% REO (including 6% Y_2O_3) in Precambrian gneiss are thought to have originated as placer accumulations (Evans, 1964). At Bald Mountain, Wyoming, a small paleoplacer monazite resource was identified in Cambrian conglomerate (Borrowman & Rosenbaum, 1962).

2.6. Other deposits

Near-economic HREE-uranium mineralization occurs as xenotime accumulations in sandstone of the late Precambrian Athabasca Group near Wheeler River in Alberta, Canada. Approximately 65 t of bastnasite concentrate were produced from a fluorspar deposit in the Gallinas Mountains, New Mexico, in the 1950s (Adams, 1965).

Marine phosphorites have been proposed as a potential source of REE (Altschuler *et al.*, 1967). Certain members of the Permian Phosphoria Formation, which are mined for phosphate in large quantities in Montana and Idaho, contain significant amounts of REE including as much as 0.1% yttrium (Gulbrandsen, 1966). Jackson and Christiansen (1993) listed 10 such phosphate deposits, all in Idaho, that together constitute a moderate-sized, low-grade REE resource (Table 1).

3. Economic factors that influence North American REE production

REE mineral concentrates and intermediate compounds had relatively steady price and production increases from the 1960s through the 1980s, when markets were created in response to new technologies while REE sources remained relatively steady. REE concentrates and intermediate compounds became relatively inexpensive when compared with many other mineral products following significant Chinese impact on the market in the 1990s. Prices for most REE commodities remained low until recently, when concerns about the supply of REE commodities used in magnets and batteries have arisen.

REE economics are complex because individual REE occur together in most deposits in fixed ratios, and producers must solve the riddle of how to balance production against market demand. This factor leads to stockpiling of unmarketable REE fractions and products by producers. For example, during the 1980s the Mountain Pass operation was able to sell most of its low-cost Ce oxide product easily (mainly into the glass industry), Sm was sold on consignment because of high demand for magnet manufacture, and Eu easily sold at high prices because of its use in color television CRTs. At the same time, the company had oversupplies of La and other REE. Strong demand for high-purity Ce, La, and Nd for use in automotive catalytic converters, fluid cracking catalysts, and magnets changed the picture during the 1990s.

In the past, REE commodities were not only mined dominantly in the USA, but also refined there. During the 1980s this began to change, particularly with the emergence of China as the dominant raw material supplier, and most REE commodities are now produced overseas. In 2003, at least 20 companies in Japan produced REE commodities that are mainly used in its domestic industries, and 16 European countries exported REE commodities to the USA in 2003.

The classification of China as a Most Favored Nation in 1978 by the USA had a strong impact on REE markets, and the US Government has shown little interest in protecting domestic producers. The Chinese government has had an aggressive policy toward the promotion of its REE industry, and during the 1990s development of Chinese REE deposits was apparently not impeded by normal market considerations, leading to significant overproduction of REE in the early 2000s. In 2003 the Chinese Government announced that it would assert control over its REE industry and restrict REE exports. Recent price increases for some REE commodities indicate that this has taken place.

Although the bastnasite produced at Mountain Pass has relatively low thorium (approximately 100 ppm), chemical processing was suspended by the California Environmental Protection Agency in 1998, mostly due to radioactive element content of waste involved in a spill incident. Between 2001 and the present, REE commodities were sold from stockpile, and imported REE commodities were tested.

The future use of REE is expected to increase, especially in automotive pollution catalysts, fluid cracking catalysts, and permanent magnets. Future growth is also forecast for REE used in lasers, fiber optics, and medical applications. Demand is expected to decline over the next decade for REE phosphors used in CRTs as flat panel display use increases. REE use in rechargeable nickel-hydride batteries may decline as lithium ion batteries gain wider use. Long-term growth is forecast for REE utilized in magnetic refrigeration alloys and other high technology uses, but such trends are difficult to predict with surety.

World REE reserves are probably sufficient to meet forecast international demand well into the 21st century. Several world-class REE deposits in Australia and China have yet to be fully developed, and contain substantial reserves. World REE markets are expected to continue to be very competitive in response to China's large resources, competitive prices, low-cost labor, inexpensive utilities, and minimal environmental and permitting requirements. China is expected to remain the world's principal REE supplier. Economic growth in several developing countries will provide new and potentially large markets in Southeast Asia and Eastern Europe.

4. Outlook for North American REE production

Because of its grade, size, and relatively simple metallurgy, the author believes that the Mountain Pass deposit of Chevron Mining Inc. remains North America's best source of REE. The main questions that must be answered regarding the future of REE production at Mountain Pass are: (i) will the Chinese government continue to control REE exports and will REE prices rise; and (ii) are there still significant American markets for REE and can Chevron Mining recapture them.

Chevron Mining recently restarted its Mountain Pass processing facilities. If this proves profitable it is likely that the company will resume mining and milling of the rich LREE-dominated carbonatite ore at Mountain Pass.

The development of new REE deposits in North America is unlikely in the near future. Undeveloped deposits with the most potential are probably the large but low-grade deposits in peralkaline igneous rocks such as the Strange Lake and Pajarito deposits. Competition with established Chinese saprolitic deposits of HREE and Y and the reportedly imminent development of the Mount Weld weathered carbonatite deposit in Australia will be a factor. Because the North American peralkaline deposits are essentially Zr deposits with HREE and Y credits, future development probably depends on the market potential for Zr.

References

Adams, J. W. (1965) Rare earths. *In* Mineral and water resources of New Mexico. New Mexico Bur. Mines. Miner. Resour. Bull., 87, 234–237.

Altschuler, Z. S., Berman, S. and Cuttitta, F. (1967) Rare earths in phosphorite: Geochemistry and potential recovery. US Geological Survey, Professional Paper 575-B, 9.

Anderson, J. L. (1983) Proterozoic anorogenic granite plutonism of North America. *In* Medaris, L. G., Mickelson, D. M., Byers, C. W. and Shanks, W. C. (eds.) Proterozoic geology. Geological Society of America, Memoir, 161, 133–154.

Armbrustmacher, T. J. (1980) Abundance and distribution of thorium in the carbonatite stock at Iron Hill, Powderhorn District, Gunnison County, Colorado. US Geological Survey, Professional Paper 1049-B, 11.

Avalon Ventures (2007) Thor Lake rare metals property. Avalon Ventures, Toronto (accessed 11 April 2007). Available from

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URL: www.avalonventures.com/key_projects/rare_industrial/thor_lake/

Barker, J. C. and Mardock, C. L. (1988) Lithophile metal, REE-Y-Nb deposits on Southern Prince of Wales Island, Alaska. *In* Carson, D. J. T. and Vassiliou, A. H. (eds.) Process mineralogy VIII. Minerals, Metals and Materials Society, Warrendale, PA, 139–158.

Borrowman, S. R. and Rosenbaum, J. D. (1962) Recovery of thorium from a Wyoming ore. U. S. Bur. Mines, Report of Investigation 5917, 8.

Castor, S. B. (1986) Mountain Pass bastnasite: Some new data. Technical Report, Mountain Pass. Molycorp, Mountain Pass, CA, 6p.

Castor, S. B. (1991) Rare earth deposits in the southern Great Basin. *In* Raines G. L., Lisle, R. E., Schafer, R. W. and Wilkinson, W. H. (eds.) Geology and ore deposits of the Great Basin. Geological Society of Nevada, Proceedings. Geological Society of Nevada, Reno, NV, 523–528.

Castor, S. B. (1993) Rare earth deposits and Proterozoic anorogenic magmatism. *In* Y. T. Maurice (ed.) Proceedings of the Quadrennial Eighth IAGOD Symposium, 1990, Ottawa, Canada. Schweizerbart'sche Verlagsbuchhandlung, E. Stuttgart, Germany, 331–340.

Castor, S. B. (1994) Rare earth minerals. *In* Carr, D. D. (ed.) Industrial minerals and rocks, 6th edn. Society for Mining, Metallurgy, and Exploration, Littleton, 827–839.

Castor, S. B. and Nason, G. W. (2004) Mountain Pass rare earth deposit, California. *In* Castor, S. B., Papke, K. G. and Meeuwig, R. O. (eds.) Proceedings of the 39th forum on the Geology of Industrial Minerals. Nevada Bureau of Mines and Geology Special Publication 33, Reno, NV, 68–81.

Chao, E. C. T., Back, J. M., Minkin, J. A., Tatsumoto, M., Wang, J., Conrad, J. E., McKee, E. H., Hou, Z., Meng, Q. and Huang, S. (1997) The sedimentary carbonate-hosted Bayan Obo REE-Fe-Nb ore deposit of Inner Mongolia, China; a cornerstone example for giant polymetallic ore deposits of hydrothermal origin. U.S. Geol. Surv. Bull. 2143, 65.

Currie, K. L. (1976) The alkaline rocks of Canada. Geol. Surv. Canada. Bull. 239, 228.

Currie, K. L. (1985) An unusual peralkaline granite near Lac Brisson, Quebec-Labrador. *In* Current research, part A. Geol. Surv. Canada., Paper 85–1A, 73–80.

DeWitt, Ed., Kwak, L. M., and Zartman, R. E. (1987) U-Th-Pb and Ar/Ar dating of the Mountain Pass carbonatite and alkalic igneous rocks, S.E. Cal. Geol. Soc. Am., 19, 642.

Drew, L. J., Meng, Q. and Sun, W. (1990) The Bayan Obo iron-rare earth-niobium deposits, Inner Mongolia, China. Lithos, 26, 43–65.

Evans, J. R. (1964) Xenotime mineralization in the Southern Music Valley area, Riverside County, California. California Division of Mines and Geology, Special Report 79, 24p.

Great Western Minerals Group (2007) Significant increase in Hoidas lake resource. Great Western Minerals Group, Saskatoon, Saskatchewan (accessed 10 April 2007). www.gwmg.ca/projects/hoidas/background.php#resources

Gulbrandsen, R. A. (1966) Chemical compositions of phosphorites of the Phosphoria Formation. Geochim. Cosmochim. Acta, 30, 769–778.

Harvey, S. E., Young, I. and Billingsley, G. (2002) Geology of the Hoidas Lake area, Ena domain, northwestern Saskatchewan. *In* Summary of Investigations 2002, Vol. 2, Miscellaneous Report 2002-4.2, Paper C-2. Saskatchewan Geological Survey, Saskatchewan Industry Resources, 13p.

Hedrick, J. B. (1999) Rare earths. *In* Minerals Yearbook 1999. US Geological Survey, Reston, VA, 60.1–60.5.

Hedrick, J. B. (2003) Rare earths. *In* Minerals Yearbook 2003. US Geological Survey, Reston, VA, 60.1–60.15.

Hedrick, J. B. (2007) Rare earths. In Mineral Commodity Summaries. US Geological Survey, Reston, VA, 130–131.

Jackson, W. D. and Christiansen, G. (1993) International strategic minerals inventory summary report: Rare-earth oxides. Circular 930-N. US Geological Survey, Reston, VA, 68p.

Kelley, V. C. (1968) Geology of alkali Precambrian rocks at Pajarito Mountain, Otero County, New Mexico. Geol. Soc. Am. Bull. 79, 1565–1572.

Kisvarsanyi, E. B., Sims, P. K. and Kisvarsanyi, G. (1989) Proterozoic ore-forming systems: Examples of iron metallogenesis from the United States mid-continent. Geol. Soc. Am. 21, A34.

Kline, M. H., Carlson, E. J., Roberston, A. F. and Storch, R. H. (1953) Bear Valley radioactive mineral placers, Valley County, Idaho. U.S. Bureau of Mines, Rep. Miner. Eval., 3130, 23p.

Mariano, A. N. (1989) Economic geology of rare earth elements. Rev. Mineral., 21, 309–337.

McKeown, F. A. and Klemic, H. (1956) Rare-earth-bearing apatite at Mineville, Essex County, New York: U. S. Geol. Surv. Bull., 1046-B, 9–23.

Metz, M. C., Brookins, D. G., Rosenberg, P. E. and Zartman, R. E. (1985) Geology and geochemistry of the Snowbird deposit, Mineral County, Montana. Econ. Geol., 80, 394–409.

Meyer, B. H. (2002) Geological exploration report of the Bear Lodge rare-earth property, Crook County, Wyoming, USA: Report prepared for Paso Rico Resources. Rare Element Resources, Vancouver (accessed 8 June 2007). Available from URL: www.rareelementresources.com

Miller, R. R. (1988) Yttrium (Y) and other rare metals (Be, Nb, REE, Ta, Zr) in Labrador. *In* Current Research 1988, Report 88-1. Newfoundland Department of Mines, Mineral Development Division, St Johns, Newfoundland, 229–245.

Nuelle, L. M., Day, W. C., Sidder, G. B. and Seeger, C. M. (1992) Geology and mineral paragenesis of the Pea Ridge iron ore mine, Washington County, Missouri; origin of the rare-earth-element- and gold-bearing breccia pipes. U. S. Geol. Surv. Bull., 1989, A1–A11.

Olson, J. C. and Hedlund, D. C. (1981) Alkalic rocks and resources of thorium and associated elements in the Powderhorn district, Gunnison County, Colorado. US Geological Survey, Reston, VA, Professional Paper 1049-C, 34p.

Olson, J. C., Pray, L. C., Shawe, D. R. and Sharp, W. N. (1954) Rare-earth mineral deposits of the Mountain Pass district, San Bernardino County, California. US Geological Survey, Reston, VA, Professional Paper 261, 75p.

Orris, G. J. and Grauch, R. I. (2002) Rare earth element mines, deposits, and occurrences. Open-File Rep. 02-189. US Geological Survey, Reston, VA, 167p.

Overstreet, W. C. (1967) The geologic occurrence of monazite. US Geological Survey, Reston, VA, Professional Paper 530, 327p.

Rare Element Resources (2005) Rare element resources reports and successful initial leach tests: October exploration field work completed, Two holes drilled. News Release, 9 November 2005. Rare Element Resources, Vancouver (accessed 8 June 2007). www.rareelementresources.com/s/NewsReleases.asp?ReportID=123194

Richardson, D. G. and Birkett, T. C. (1996) Peralkaline rock-associated rare metals. *In* Eckstrand, O. R., Sinclair, W. D. and Thorpe, R. I. (eds.) Geology of Canadian mineral deposit types. Geology of Canada, no. 8. Geological Survey of Canada, Ottawa, 523–540.

Robertson, J. A. (1981) The Blind River uranium deposits: The ores and their setting. *In* Armstrong, F. C. (ed.) Genesis of U- and . US Geological Survey, Reston Au-bearing Quartz-pebble Conglomerates, Professional Paper 1161, U1–U23.

Roeder, P. K., MacArthur, D., Ma, X., Palmer, G. R. and Mariano, J. N. (1987) Cathodoluminescence and microprobe study of rare earth elements in apatite. Am. Mineral., 72, 801–811.

Roscoe, S. M. (1969) Huronian rocks and uraniferous conglomerates. Geological Survey of Canada, Ottawa, Paper 68-40, 205p.

Sherer, R. L. (1990) Pajarito yttrium-zirconium deposit, Otero County, New Mexico. New Mexico Geol., 12, 21.

Staatz, M. H. (1983) Geology and description of thorium and rare-earth deposits in the southern Bear Lodge Mountains, northeastern Wyoming. US Geological Survey, Reston, VA, Professional Paper 1049-D, 51p.

Staatz, M. H., Sharp, B. J. and Hetland, D. L. (1979) Geology and thorium resources of the Lemhi Pass thorium District, Idaho and Montana. US Geological Survey, Reston, VA, Professional Paper 1049-A, 90p.

Taylor, R. P. and Pollard, P. J. (1996) Rare earth element mineralization in peralkaline systems; the T-zone-REE-Y-Be deposit, Thor Lake, Northwest Territories, Canada. *In* Jones, A. P., Wall, F., and Williams, C. T. (eds.) Rare earth minerals: Chemistry, origin and ore deposits. Mineralogical Society Series no. 7. Chapman and Hall, London, 167–192.

Trueman, D. L., Pedersen, J. C., de St Jorre, L. and Smith, D. G. W. (1988) The Thor Lake rare-metal deposits. Northwest Territories. *In* Taylor, R. P. and Strong, D. F. (eds.). Can. Inst. MinRecent advances in the geology of Granite-related mineral deposits. Metal., 39, 280–290.

Vallee, M. and Dubuc, F. (1970) The St-Honoré carbonatite deposit, Quebec. Can. Inst. Min. Metal. Trans., 73, 346–356.

Wall, F. and Mariano, A. N. (1996) Rare earth minerals in carbonatites: A discussion centered on the Kangankunde carbonatite, Malawi. *In* Jones, A. P., Wall, F. and Williams, C. T. (eds.) Rare earth minerals: Chemistry, origin and ore deposits. Mineralogical Society Series no. 7. Chapman and Hall, London, 193–225.

Woolley, A. R. (1987) Alkaline rocks and carbonatites of the world. Part 1: North and South America. University of Texas Press, Austin, Texas, 216p.

Wu, C., Yuan, Z. and Bai, G. (1996) Rare earth deposits in China. *In* Jones, A. P., Wall, F. and Williams, C. T. (eds.) Rare earth minerals: Chemistry, origin and ore deposits. Mineralogical Society Series no. 7. Chapman and Hall, London, 281–310.

Yuan, Z., Bai, G., Wu, C., Zhang, Z. and Ye, X. (1992) Geological features and genesis of the Bayan Obo REE ore deposit, Inner Mongolia, China. Appl. Geochem., 7, 429–442.