

## Chapter 2

# The Ore Minerals and Major Ore Deposits of the Rare Earths

**Abstract** This chapter gives an overview of the major and minor ore minerals of the rare earths, and of the related major ore deposits. As most of the rare earths are mined in China, the impression may arise that ore deposits of these metals occur in few other places on Earth. However, nothing is less true. The extensive overview of the ore deposits of the rare earths in this chapter is especially meant to indicate that deposits occur in quite a variety of countries, and that the apparent dominance of China is economically (and politically) powered.

## 2.1 Major Ore Minerals

At this date, the principal ore minerals for the REEs are *monazite*, *bastnaesite*,<sup>1</sup> and *xenotime*. The first REE mineral to be used was gadolinite, and from this mineral, several of the REE were first isolated, but it was not applied on an industrial scale. The first REE ore mineral from which REE were extracted for industrial use was monazite.

### 2.1.1 Monazite

Monazite (Breithaupt 1829) has a generalized chemical formula  $\text{CePO}_4$ . The name is derived from the Greek *monazeis*, meaning “to be alone” because of the isolated crystals of monazite, and the fact that it was quite rare when first found. For an image, see Fig. 2.1. Besides Ce, also other REE occur in monazite. These are mostly the LREEs (Light Rare Earth Elements: La, Ce, Pr, Nd, and Sm. Invariably, a mix of rare earths is present. The suffix Ce, La, Nd, or Pr is added to denote the

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<sup>1</sup>Bastnaesite is also spelled bastnäsite, or bastnasite. In this book, the more common spelling bastnaesite will be used.



**Fig. 2.1** Monazite, Iveland Setesdal, Norway. From the collection of Naturalis Biodiversity Center, Leiden, The Netherlands, Sample RGM412064. *Photograph* Naturalis. Used with permission

most frequently occurring REE. It usually also contains Th and/or U, but the amounts in monazite are generally too low to be extracted as a valuable by-product.

Monazite occurs generally as a minor mineral in granites and granodiorites and associated pegmatites, and also occurs in many metamorphic rocks.

Because monazite is:

- (a) a heavy mineral with a specific gravity ranging between 4.8 and 5.5, with an average of 5.15 (Webmineral 2014), and
- (b) very resistant to weathering,

it concentrates after weathering of the igneous or metamorphic host rock and subsequent transport in placers and heavy mineral sands (Gupta and Krishnamurthy 2005).

### 2.1.2 Bastnaesite

Bastnaesite (Fig. 2.2) was first described by the Swedish chemist Wilhelm Hisinger as “basis-fluor-cerium”, from the Bästnas mine near Riddarhyttan, Västmanland, Sweden (Hisinger 1838). The general formula of bastnaesite is  $\text{Ce}(\text{CO}_3)\text{F}$ . Bastnaesite is another major REE ore mineral containing mostly the LREEs cerium, lanthanum, praseodymium, and neodymium. Of the HREEs, only Y is regularly found. A suffix Ce, La, Nd or Y is always added before the name to indicate the dominant REE. Low proportions of other HREEs are present. Also hydroxyl bearing versions exist: hydroxylbastnaesite-(Ce) and hydroxylbastnaesite-(Nd).

Bastnaesite, containing neither U nor Th, has replaced monazite as the primary LREE-ore mineral. Related minerals may arise from substitution of the fluorine and carbonate ions. Bastnaesite is a widespread mineral, although it never occurs in



**Fig. 2.2** Bastnaesite (*yellowish material*), Mountain Pass California. Sample from the collection of Naturalis Biodiversity Center, Leiden, The Netherlands. Sample ST 82224. Photograph by J.H.L. Voncken. Used with permission

large quantities. It occurs in a variety of igneous rocks, such as carbonatites,<sup>2</sup> vein deposits, contact metamorphic rocks, and pegmatites (Gupta and Krishnamurthy 2005). Major ore deposits are generally related to carbonatite intrusions. Carbonatites are often found in relation to alkaline intrusives.

### 2.1.3 Xenotime

Xenotime (Fig. 2.3) was first described by Berzelius in a specimen from Hydra (Hitterø), Flekkefjord, Vest-Agder, Norway (Berzelius 1824, 1825). The name is derived from the Greek *xenos*—“foreign” and *time*—“honor”. The generalized chemical formula of xenotime is  $(YPO_4)$ . Xenotime, in contrast to monazite and bastnaesite, generally contains, besides Y, appreciable amounts of the HREE (Heavy Rare Earth Elements: Y, Tb, Dy, Ho, Er, Tm, Yb, and Lu). Xenotime may contain up to 67 % REO, mostly the heavier elements (Gupta and Krishnamurthy 2005). Most often occurring are dysprosium, ytterbium, erbium, and gadolinium. Xenotime contains lesser quantities of terbium, holmium, thulium, and lutetium. Xenotime is the major source for HREE (Table 2.1), but like monazite also contains Th and/or U, which, depending on the location of the deposit, and the concentration of these two elements in the mineral, may be a by-product or a pest.

For instance, Förster (1998a, b) list compositional variations of xenotimes and monazites from the German Erzgebirge/Fichtelgebirge, showing that xenotime

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<sup>2</sup>Carbonatite is a rare igneous carbonate rock (almost invariably intrusive), consisting of more than 50 % carbonate minerals. Worldwide, only one example of extrusive rocks is known: the rocks and lavas of the (active) Ol Doinyo Lengai volcano, Tanzania.

**Fig. 2.3** Xenotime, Madagascar. From the collection of Naturalis Biodiversity Center, Leiden, The Netherlands, Sample RGM412055. *Photograph* Naturalis. Used with permission



tends to concentrate the HREEs (Gd, Tb, Dy, Ho, Er, Yb, Lu), whereas monazite tends to concentrate the LREEs (La, Ce, Pr, Nd, Sm).

Xenotime is an accessory mineral in pegmatites and other (non-basic) igneous rocks, but also is common in metamorphic rocks. Xenotime, being very similar to monazite (e.g. Gratz and Heinrich 1997), also has a high specific gravity, in the range 4.4–5.1, with an average of 4.75 (Webmineral 2014), and also concentrates in placers and heavy mineral sands. However, such deposits are not widespread (Gupta and Krishnamurthy 2005).

In Table 2.1 examples of typical compositions of monazite, xenotime and bastnaesite are given.

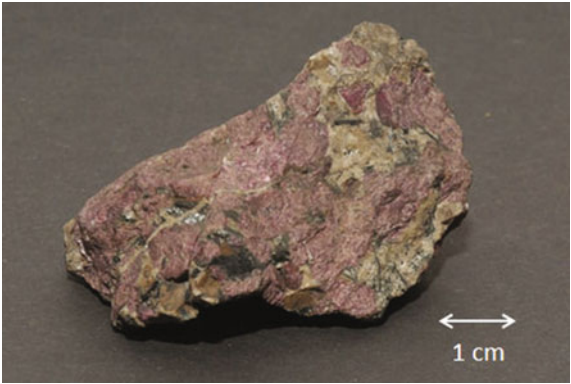
With respect to the actinides, monazite tends to concentrate thorium, whereas xenotime tends to concentrate uranium, but can take up also appreciable amounts of thorium. According to Deer et al. (2013), common varieties of monazite have 4–12 mol% of  $\text{ThO}_2$ , whereas uranium occurs in minor amounts. Van Emden et al. (1997) mention  $\text{ThO}_2$  contents in monazite ranging 1.2–21.9 wt%, whereas  $\text{UO}_2$  contents are from detection limit up to 0.75 wt%. Xenotime analyses show  $\text{UO}_2$  contents ranging from detection limit to 5.82 wt%, while  $\text{ThO}_2$  varies from detection limit to 8.44 wt%. Watt (1995) lists monazite compositions showing wt% of Th to vary from 5.17–21.41 wt%, and  $\text{UO}_2$  from 0.22–3.17 wt%.

### 2.1.4 Eudialyte

Eudialyte (Fig. 2.4) was first described by Klaproth (1810). Eudialyte is a cyclosilicate with the general formula  $\text{Na}_4(\text{Ca}, \text{Ce})_2(\text{Fe}^{2+}, \text{Mn}^{2+})\text{ZrSi}_8\text{O}_{22}(\text{OH}, \text{Cl})_2$ . The name is from the Greek, meaning readily decomposable, referring to its easy dissolution in acids (Handbook of Mineralogy 2001; Anthony et al. 2014; Mindat.org 2014). Igneous eudialyte occurs in undersaturated alkaline intrusions and

**Table 2.1** Examples of typical compositions of monazite, xenotime, and bastnaesite (Webmineral 2014)

Element	Monazite-Ce	Monazite-La	Xenotime-Y
La <sub>2</sub> O <sub>3</sub>	16.95	33.95	–
Ce <sub>2</sub> O <sub>3</sub>	34.16	17.10	–
ThO <sub>2</sub>	5.50	5.50	–
P <sub>2</sub> O <sub>5</sub>	29.55	29.58	38.60
Nd <sub>2</sub> O <sub>3</sub>	14.01	14.03	–
Y <sub>2</sub> O <sub>3</sub>	–	–	61.40
CO <sub>2</sub>	–	–	–
F	–	–	–
O = F <sub>2</sub>	–	–	–
Total	100.17	100.17	100.00
Element	Bastnaesite-Ce	Bastnaesite-La	Bastnaesite-Y
La <sub>2</sub> O <sub>3</sub>	–	74.76	
Ce <sub>2</sub> O <sub>3</sub>	74.90	–	
ThO <sub>2</sub>	–	–	
P <sub>2</sub> O <sub>5</sub>	–	–	
Nd <sub>2</sub> O <sub>4</sub>	–	–	
Y <sub>2</sub> O <sub>3</sub>	–	–	67.24
CO <sub>2</sub>	20.08	20.20	26.21
F	8.67	8.72	11.31
O = F <sub>2</sub>	–3.65	–3.67	–4.76
Total	100.00	100.00	100.00



**Fig. 2.4** Eudialyte (*reddish material*), Kangerdlugssuaq fjord, Greenland. From the collection of Naturalis Biodiversity Center, Leiden The Netherlands, Sample RGM1055008. *Photograph* Naturalis. Used with permission

**Table 2.2** Two typical eudialyte compositions (Handbook of Mineralogy 2001)

Element	Kipawa Lake, Canada wt%	Khibiny Massif, Russia wt%
SiO <sub>2</sub>	50.35	50.14
TiO <sub>2</sub>	0.38	0.46
ZrO <sub>2</sub>	11.80	11.83
Al <sub>2</sub> O <sub>3</sub>	0.44	0.07
RE <sub>2</sub> O <sub>3</sub>	6.40	0.37
Fe <sub>2</sub> O <sub>3</sub>	0.19	0.50
Nb <sub>2</sub> O <sub>5</sub>	0.69	0.11
FeO	2.41	5.32
MnO	1.34	0.60
MgO	0.13	0.24
CaO	9.74	11.18
SrO	0.11	0.47
Na <sub>2</sub> O	12.53	14.06
K <sub>2</sub> O	0.43	1.39
F	0.23	
Cl	1.47	1.82
H <sub>2</sub> O <sup>+</sup>	1.64	1.07
H <sub>2</sub> O <sup>-</sup>		0.12
P <sub>2</sub> O <sub>5</sub>	0.03	
S		0.04
-O = (F, Cl) <sub>2</sub>	0.43	0.41
Total	99.88	99.38

**Table 2.3** REE-content of eudialyte (Harris et al. 1982)

REE <sub>2</sub> O <sub>3</sub>	wt%
Y <sub>2</sub> O <sub>3</sub>	3.61
La <sub>2</sub> O <sub>3</sub>	1.13
Ce <sub>2</sub> O <sub>3</sub>	2.37
Pr <sub>2</sub> O <sub>3</sub>	0.27
Nd <sub>2</sub> O <sub>3</sub>	1.12
Sm <sub>2</sub> O <sub>3</sub>	0.29
Gd <sub>2</sub> O <sub>3</sub>	0.69
Dy <sub>2</sub> O <sub>3</sub>	0.52
Er <sub>2</sub> O <sub>3</sub>	0.48
Yb <sub>2</sub> O <sub>3</sub>	0.18
Total	10.66

associated pegmatites (Deer et al. 1986a). Two typical eudialyte compositions are given in Table 2.2 (Handbook of Mineralogy 2001).

Harris et al. (1982) give the following concentrations for REEs in REE-rich eudialyte from Ascension Island (Table 2.3).

## 2.2 Minor REE Minerals

Other REE-minerals are numerous, but usually unimportant for industrial REE-extraction. In Table 2.4 a list of the other REE-containing minerals known up to now is given (Tasman Metals 2014a; Mindat.org 2014 Webmineral.com 2014). Like the major REE-minerals, for many minor REE-minerals several analogues

**Table 2.4** Minor REE minerals

Mineral name	Formula
Aeschynite	$(\text{Ce, Ca, Fe})(\text{Ti, Nb})_2(\text{O, OH})_6$
Aenigmatite	$(\text{Na, Ca})_4(\text{Fe, Ti, Mg})_{12}\text{Si}_{12}\text{O}_{40}$
Allanite (Orthite)	$(\text{Ca, Ce})(\text{Al, Fe}^{2+})(\text{Si}_2\text{O}_7)(\text{SiO}_4)\text{O}(\text{OH})$
Ancylite	$\text{SrCe}(\text{CO}_3)_2(\text{OH}) \cdot (\text{H}_2\text{O})$
Apatite	$\text{Ca}_5(\text{PO}_4)_3\text{F}$ Apatite is as such not a rare earth mineral, but REEs may concentrate them, in which case they substitute for Ca
Brannerite	$(\text{U, Ca, Ce})(\text{Ti, Fe})_2\text{O}_6$
Britholite	$\text{Ca}_2(\text{Ce, Ca})_3(\text{SiO}_4, \text{PO}_4)_3(\text{OH, F})$
Cerite	$(\text{Ce, La, Ca})_9(\text{Mg, Fe})(\text{SiO}_4)_3(\text{HSiO}_4)_4(\text{OH})_3$
Cerianite	$(\text{Ce, Th})\text{O}_2$
Cheralite	$(\text{Ca, Ce})(\text{Th, Ce})(\text{PO}_4)_2$
Churchite	$\text{YPO}_4 \cdot 2(\text{H}_2\text{O})$
Euxenite	$(\text{Y, Ce, Ca})(\text{Nb, Ta, Ti})_2\text{O}_6$
Fergusonite	$\text{Y}(\text{Nb, Ti})\text{O}_4$
Florencite	$(\text{Ce, La})\text{Al}_3(\text{PO}_4)_2(\text{OH})_6$
Gadolinite	$\text{Y}_2\text{Fe}^{2+}\text{Be}_2\text{Si}_2\text{O}_{10}$
Huanghoite	$\text{BaCe}(\text{CO}_3)_2\text{F}$
Hydroxylbastnaesite	$(\text{Ce, La, Nd})\text{CO}_3(\text{F, OH})$
Kainosite	$\text{Ce}_2(\text{Y, Ce})_2(\text{Si}_4\text{O}_{12})(\text{CO}_3) \cdot \text{H}_2\text{O}$
Loparite	$(\text{Na, Ce, Ca, Sr, Th})(\text{Ti, Nb, Fe})\text{O}_3$
Mosandrite	$\text{Na}(\text{Na, Ca})_2(\text{Ca, Ce, Y})_4(\text{Ti, Nb, Zr})(\text{Si}_2\text{O}_7)_2(\text{O, F})_2\text{F}_3$
Parisite	$\text{Ca}(\text{Ce, La})_2(\text{CO}_3)_3\text{F}_2$
Rinkite	$(\text{Na, Ca})_3(\text{Ca, Ce})_4\text{Ti}(\text{Si}_2\text{O}_7)_2\text{OF}_3$
Samarskite	$(\text{Y, Fe}^{3+}, \text{U})(\text{Nb, Ta})_5\text{O}_4$
Synchisite	$\text{Ca}(\text{Ce, Nd, Y})\text{CO}_3\text{F}$
Steenstrupine	$\text{Na}_{14}\text{Ce}_6\text{Mn}^{2+}\text{Mn}^{3+}\text{Fe}_2^{2+}(\text{Zr, Th})(\text{Si}_6\text{O}_{18})_2(\text{PO}_4)_7 \cdot 3(\text{H}_2\text{O})$
Tengerite	$\text{Y}_2(\text{CO}_3)_3 \cdot 2-3(\text{H}_2\text{O})$
Thalenite	$\text{Y}_3\text{Si}_3\text{O}_{10}(\text{OH})$
Yttrotantalite	$(\text{Y, U, Fe})(\text{Ta, Nb})\text{O}_4$
Zircon	$\text{ZrSiO}_4$ . Zircon also is not a rare earth mineral as such, but like apatite, it may concentrate REEs, in which case they substitute for Zr

exist, because several of the REEs may substitute for one another. These minerals are then indicated with a suffix for the predominating REE, and every single one is another mineral. For instance, for *aeschynite*, there are defined: *aeschynite-Ce*, *aeschynite-Nd*, and *aeschynite-Y*.

*Allanite* is a disilicate (sorosilicate) mineral from the epidote group, with the general formula  $(\text{Ca}, \text{Ce})(\text{Al}, \text{Fe}^{2+})(\text{Si}_2\text{O}_7)(\text{SiO}_4)\text{O}(\text{OH})$ . It is named for the Scottish mineralogist Thomas Allan (1777–1833). Allanite was described by Thomson (1810). Allanite is also called orthite (synonym). Igneous allanite occurs in granite, granodiorite, monzonite and syenite intrusions. Allanite may contain up to 20 wt% of REE, expressed as  $\text{REE}_2\text{O}_3$ . This appears to be mostly  $\text{La}_2\text{O}_3 + \text{Ce}_2\text{O}_3$ , although from the LREEs also  $\text{Nd}_2\text{O}_3$  is reported in concentrations up to approximately 3 wt% (Deer et al. 1986b). Other REEs occurring in allanite are:  $\text{Dy}_2\text{O}_3$  (up to 0.21 %), although Deer et al. also report one analysis from 1940 with an unlikely amount of 6.96 wt%), Sm, and Gd (up to 1.2 wt%  $\text{REE}_2\text{O}_3$ ). The REEs replace Ca. Allanite may contain up to 5 wt%  $\text{ThO}_2$ .  $\text{UO}_2$  occurs up to 0.5 wt% (Deer et al. 1986b, 2013).

## 2.3 REE-Containing Rocks

REE are often associated with a carbonate rock called carbonatite: an igneous (generally intrusive) rock consisting of more than 50 % carbonate minerals (carbonates of Ca, Mg, Na and Fe). Carbonatites as such are closely related to continental alkaline rocks (McBirney 1993). These are a group of rare (alkaline) igneous rocks that have an ultramafic or mafic silica-depleted character. Alkaline rocks are important for their high concentrations of incompatible or so-called Large-Ion-Lithophile elements (LIL-elements). Among others, these elements are the metals niobium (Nb), tantalum (Ta), and the rare earth elements (REE). Alkaline igneous rocks occur in several geological settings.

## 2.4 Ore Deposits of the Rare Earths

The deposits mentioned here are currently (2015) the most well-known economically interesting REE deposits. An extended list of economic and non-economic REE-occurrences can be found in Orris and Grauch (2002). Recently, ion adsorption deposits, quite similar to those in southern China have been discovered on the island of Madagascar (Desharnais et al. 2014). Also it is likely that more deposits will be found in the future. Deposits described in this work are listed in Table 2.5. The descriptions given here are of course by no means exhaustive.



**Table 2.5** REE-deposits described/mentioned in this chapter

Deposit	Location	Type	Main REE	REE-mineral(s)
Mountain Pass	California, USA	Carbonatite	La, Ce, Nd	Bastnaesite
Bayan Obo	Inner Mongolia, China	Carbonatite/hydrothermal	LREE	Bastnaesite, parisite, monazite
Mount Weld	SW-Australia	Laterite/carbonatite	LREE	Apatite, monazite, synchysite, churchite, plumbogummite-group minerals
Ilimaussaq ( <i>Kvanefeldt, Kringsjærne, Motzfeldt Sø</i> )	Greenland (Denmark)	Peralkaline igneous	La, Ce, Nd, HREE	Eudialyte, steenstrupine
Pilanesberg	South Africa	Peralkaline igneous	Ce, La	Eudialyte
Steenkampsraal	South Africa	Vein	La, Ce, Nd	Monazite, apatite
Hoidas Lake	Canada	Vein	La, Ce, Pr, Nd	Apatite, allanite
Thor lake	Canada	Alkaline igneous	La, Ce, Pr, Nd, HREE	Bastnaesite
Strange Lake and Misery Lake	Canada	Alkaline igneous / hydrothermal	La, Ce, Nd, HREE	Gadolinite, bastnaesite
Nolans Bore	Australia	Vein	La, Ce, Nd	Apatite, allanite
Norra Kärr	Sweden	Peralkaline igneous	La, Ce, Nd, HREE	Eudialyte
Khibina and Lovozero	Russia, Kola Peninsula	Peralkaline igneous	LREE + Y, minor HREE	Eudialyte, apatite
Nkwombwa Hill	Zambia	Carbonatite	LREE	Monazite, bastnaesite
Kagankunde	Malawi	Carbonatite	LREE	Monazite-Ce, bastnaesite-Ce
Tundulu	Malawi	Carbonatite	LREE	Synchesite, parisite, bastnaesite
Songwe	Malawi	Carbonatite	LREE, especially Nd	Synchysite, apatite

(continued)

Table 2.5 (continued)

Deposit	Location	Type	Main REE	REE-mineral(s)
Chinese ion adsorption deposits	South China	Soils	La, Nd, HREE	Clay minerals
Maoniuping	Sichuan, China	Carbonatite	LREE	Bastnaesite
Dong Pao	Vietnam	Carbonatite	LREE	Bastnaesite, parisite
Deep Sea	Pacific Ocean	Crusts, pelagic muds		



**Fig. 2.5** The location of the Mountain Pass deposit (*orange balloon*). Modified after Google Maps (2015). The city of Los Angeles in the center on the bottom of the map

### 2.4.1 Mountain Pass

For a long time, the major ore deposit for rare earths was the Mountain Pass deposit, in California, USA (Fig. 2.5).

Geological prospecting in the area started already in 1861, but the most important discovery, that of the rich REE-deposit, was made much later. During a prospect for uranium in 1949, a strongly radioactive outcrop of a vein, close to the shaft of the Sulphide Queen lead and gold mine, was found. The vein contained a large amount of a light-brown heavy mineral, identified as bastnaesite (Fig. 2.2). Finding many other veins in the area, and all of the material being radioactive, it was concluded that a large amount of bastnaesite, associated with some thorium-bearing minerals, must be present in the area (Hewett 1954).

The Molybdenum Corporation of America<sup>3</sup> bought the rights to the ore bodies in February 1950. Later that year, the company started to sink a shaft (Hewett 1954). Many more veins with rare earth minerals were found in the surrounding hills.

In 1950, J. C. Olson of the USGS and D.F. Hewett started to make a geological map of the area. They also found a large body of a carbonate type of rock, with relatively high amounts of barite ( $\text{BaSO}_4$ ), about 20 %. The carbonate rock mass was called the Sulphide Queen carbonate body. Laboratory investigations showed

<sup>3</sup>The Molybdenum Corporation of America changed its name to *Molycorp* in 1974. The corporation was acquired by *Union Oil* in 1977, which in turn became part of *Chevron Corporation* in 2005. (Molycorp 2014; [www.molycorp.com](http://www.molycorp.com)). In 2008, Chevron sold the Mountain Pass mine to the privately held *Molycorp Minerals LLC*.

**Table 2.6** Mean composition of Mountain Pass concentrate (Castor 2008)

Oxide	(wt%)
$\text{La}_2\text{O}_3$	33.79
$\text{CeO}_2$	49.59
$\text{Pr}_6\text{O}_{11}$	4.12
$\text{Nd}_2\text{O}_3$	11.16
$\text{Sm}_2\text{O}_3$	0.85
$\text{Eu}_2\text{O}_3$	0.105
$\text{Gd}_2\text{O}_3$	0.21
$\text{Tb}_4\text{O}_7$	0.016
$\text{Dy}_2\text{O}_3$	0.034
$\text{Ho}_2\text{O}_3$	0.034
$\text{Er}_2\text{O}_3$	0.006
$\text{Tm}_2\text{O}_3$	0.002
$\text{Yb}_2\text{O}_3$	0.002
$\text{Y}_2\text{O}_3$	0.13
Total	100.049



**Fig. 2.6** Sövite. Alnö alkaline and carbonatite ring complex, Sweden. From the collection of Naturalis Biodiversity Center Leiden, The Netherlands, Sample RGM387008.0. *Photograph* J.H. L. Voncken. Used with permission

that a large proportion of the entire barite-carbonate rocks contains 5–15 % bastnaesite.

Although for the carbonate rocks at Mountain Pass alongside a magmatic origin, a sedimentary origin was considered, it finally became clear that the carbonate body was of igneous origin (Olson et al. 1954).

The mean composition of concentrate from Mountain Pass is given in Table 2.6. Figure 2.6 shows an example of a carbonatite rock type, called sövite.

**Fig. 2.7** Location of the Bayan Obo deposit. Modified after Drew et al. (1990) and Wikipedia (2014)



### 2.4.2 Bayan Obo, Inner Mongolia, China

Inner Mongolia is an autonomous region of China, bordering Mongolia and Russia. The location of Bayan Obo is indicated in Fig. 2.7. It is the largest mining town in the province. The name Bayan Obo is also spelled Baiyun-Obo or Baiyun Ebo (Encyclopedia Britannica online 2014; Mindat.org 2014).

The deposit is located in the sediments of the Bayan Obo group. This group of rocks consists of low-grade metamorphic sandstones, siltstones, limestones, and dolomites. The ore deposits occur in a synclinal structure, termed the Bayan syncline (or Kuan syncline, Yang et al. 2009), in meta-sedimentary dolomite<sup>4</sup> marble with quartzite beds (in local stratigraphy called the H8-unit), which in turn is covered by shale. This dolomite marble is of Middle Proterozoic age (Chao et al. 1997). The ore bodies at Bayan Obo occur as hydrothermal replacements of the dolomite marble. The shale overlying the dolomite apparently acted as a seal for the later hydrothermal fluids that caused the mineralization (Drew et al. 1990).

It must also be mentioned here that the Bayan Obo ores are not only REE-ores. There also is significant mineralization of iron ore (Fe) and of niobium (Nb). Ore reserves are: approximately 1500 million metric tons of iron ore with an average grade of 35 %; 1 million tons of niobium ore with an average grade of 0.13 %; and at least 48 million tons of rare earth oxides with an average grade of 6 % (Drew et al. 1990). The deposit was discovered in 1927. Mining, not for REE or Nb, but for iron began in 1957.

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<sup>4</sup>Dolomite rock is defined as a carbonate rock, containing calcite <50 %, dolomite >50 %. (Visser 1980). The term dolostone has been coined to avoid confusion with the mineral dolomite, CaMg (CO<sub>3</sub>)<sub>2</sub>, but has not gained general acceptance.

**Table 2.7** Average REE-composition of Bayan Obo ore (Zhi Li and Yang 2014)

Oxide	wt%
La <sub>2</sub> O <sub>3</sub>	24–26
CeO <sub>2</sub>	50
Pr <sub>6</sub> O <sub>11</sub>	3–5
Nd <sub>2</sub> O <sub>3</sub>	16–18
Sm <sub>2</sub> O <sub>3</sub>	1.5
Eu <sub>2</sub> O <sub>3</sub>	0.2
Gd <sub>2</sub> O <sub>3</sub>	0.4
(Tb–Lu) <sub>2</sub> O <sub>3</sub>	0.2–0.3
Y <sub>2</sub> O <sub>3</sub>	0.3

Most researchers agree that the ores themselves are formed by hydrothermal alteration (Yang et al. 2009; Yang and Le Bas 2004; Drew et al. 1990; Qiao et al. 1997; Chao et al. 1997). The origin of the hydrothermal fluid is either a mantle derived carbonatitic magma (Zhang et al. 2002) or related to (carbonatitic) magma generation as a result of subduction (Drew et al. 1990).

Wang et al. (1994) found an age window of 450–555 Ma for the formation of the deposit, which is approximately early Cambrian to late Ordovician.

The average composition of the ore is given in Table 2.7.

### 2.4.3 Mount Weld, South-West Australia

Mount Weld is located 35 km south of Laverton, Western Australia (Fig. 2.8). The rare-earth-element deposit was discovered in 1988, but was not exploited for a long time, because China was supplying REE at low prices. When the so-called REE-crisis (see Chap. 6) came about in 2009, Lynas Corporation,<sup>5</sup> the company owning the deposit, decided to exploit the rich REE-deposit.

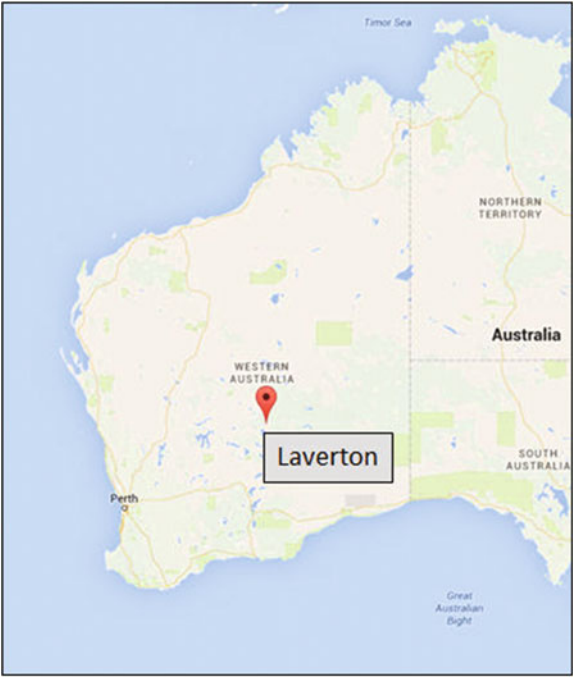
In January 2012, the Mineral Resource estimate for Mount Weld was 23.9 million tons, at an average grade of 7.9 % REO, for a total of 1.9 million tons REO.

The Mount Weld carbonatite dates from the Proterozoic (approximately 2025 Ma ago) and is emplaced in the Yilgarn Craton (Hoatson et al. 2011). The carbonatite is covered by a thick lateritic soil, which in its turn is covered by lacustrine and alluvial sediments (Lottermoser 1990). The Mount Weld deposit occurs in the weathered layer.

The primary igneous REE-bearing minerals are apatite, monazite, and synchysite (Willett et al. 1989; Lottermoser 1990). Secondary minerals containing REEs are

<sup>5</sup><https://www.lynascorp.com/Pages/home.aspx>.

**Fig. 2.8** The location of Laverton in SW-Australia. Modified after Google Maps (2015)



**Table 2.8** Average composition of the ore from Mount Weld (Lynas Corporation 2013)

Oxide	wt%
La <sub>2</sub> O <sub>3</sub>	25.50
CeO <sub>2</sub>	46.74
Nd <sub>2</sub> O <sub>3</sub>	18.50
Pr <sub>6</sub> O <sub>11</sub>	5.32
Sm <sub>2</sub> O <sub>3</sub>	2.27
Dy <sub>2</sub> O <sub>3</sub>	0.12
Eu <sub>2</sub> O <sub>3</sub>	0.44
Tb <sub>2</sub> O <sub>3</sub>	0.07

Fe-oxyhydroxides, secondary monazite, churchite, and plumbogummite<sup>6</sup>-group minerals.

At Mount Weld, the bulk of the REE and Y are incorporated in secondary monazite, churchite and a plumbogummite-group mineral. The LREE preferentially enter (secondary) monazite, whereas the HREEs are mostly found in churchite.

The average composition of the ore is given in Table 2.8.

<sup>6</sup>Plumbogummite is PbAl<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>(OH)<sub>5</sub>·H<sub>2</sub>O.

### 2.4.4 Ilímaussaq Alkaline Complex, South Greenland

Of a completely different nature is the Ilímaussaq complex in South-West Greenland. The complex is related to so-called alkaline igneous rocks. Alkaline igneous rocks are defined in terms of their alkali ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ) content and silica content. For definitions see for instance Sørensen (1974) and Streckeisen (1967, 1980). In terms of volume, alkaline igneous rocks make up less than one percent of all igneous rocks (Fitton and Upton 1987). They have, however, been studied intensively, because of their peculiar mineralogy, and the association of these rocks with so-called *large ion lithophile elements* or LILE's. Among these elements are *niobium*, *tantalum*, and the *rare earth elements*. Also they may be associated with economic deposits of *apatite* and *diamonds* (Fitton and Upton 1987). The most important occurrences of alkaline igneous rocks are found in continental rift valleys. The best studied occurrence is the Proterozoic Gardar Province in West Greenland, containing the Ilímaussaq complex.

The Ilímaussaq Complex is the type locality of the so-called *agpaitic magmatism*. Agpaitic rocks are peralkaline nepheline syenites with complex Zr, Ti and REE minerals, such as eudialyte, steenstrupine, rinkite and mosandrite, rather than for instance zircon and ilmenite (Sørensen 1992, 1997). Other prominent minerals are aenigmatite<sup>7</sup> and astrophyllite.<sup>8</sup>

The age of the complex has been determined by several researchers. Ages found range between:  $1130 \pm 50$  Ma, and  $1168 \pm 21$  Ma (Sørensen 2001; Blaxland et al. 1976). This latter age is on the border between the Paleoproterozoic and the Middle Proterozoic.

Ilímaussaq has large resources of uranium, rare earth elements and zinc. The complex is located close to existing infrastructure in southern Greenland, making exploitation of the mineral resources favorable (Greenland Minerals and Energy 2014). The location of the complex is shown in Fig. 2.9. In the Ilímaussaq complex, we find two very high-quality ore deposits for rare earth elements: Kvanefjeld and Kringlerne. The nearby Igaliko nepheline syenite complex (age: 1273 Ma) hosts the Motzfeld deposit.

#### 2.4.4.1 Kvanefjeld

Kvanefjeld was discovered in the 1950s. and was extensively studied during the 1960s, 70s and 80s. The main REE-ore mineral is steenstrupine. The Kvanefjeld REE deposit is dominated by Ce (approx. 40 %), La (approx. 25 %), Nd (approx. 15 %), Y (approx. 10 %), Pr (approx. 5 %), with the HREE making up the remaining 5 %.

<sup>7</sup>Aenigmatite is  $\text{Na}_2\text{Fe}_5^{2+}\text{TiSi}_6\text{O}_{20}$ .

<sup>8</sup>Astrophyllite is  $\text{K}_2\text{Na}(\text{Fe}, \text{Mn})_7\text{Ti}_2\text{Si}_8\text{O}_{26}(\text{OH})_4$ .



**Fig. 2.9** Greenland with the location of Ilímaussaq. Modified after Google Maps (2015)



The total amount of REE-resources is 619 Mt, composed of both indicated resources of 437 Mt and inferred resources of 182 Mt (Sørensen and Kalvig 2011).

#### 2.4.4.2 Kringlerne (a.k.a. Tanbreez)

The Kringlerne deposit occurs in the lower cumulates of the layered agpaitic nepheline syenites. The cumulates consist of 29 cyclic layers, which amount to a total thickness of about 200 m. They are composed of black arfvedsonite dominated syenite, reddish eudialyte dominated syenite and whitish feldspar dominated syenite (Sørensen and Kalvig 2011).

The deposit contains 1000 Mt grading 2 %  $\text{ZrO}_2$ , 0.25 %  $\text{Nb}_2\text{O}_5$ , 0.5 % REO, 0.1 %  $\text{Y}_2\text{O}_3$  and 0.025 %  $\text{Ta}_2\text{O}_5$ . The distribution of light and heavy REEs in eudialyte is reported to be 88 % and 12 % respectively (GEUS 2011). Kringlerne is considered to be very rich in HREE (Tanbreez 2014).

The deposit is now also referred to as Tanbreez, after the company that is exploiting it (Tanbreez Mining Greenland A/S). The name **Tanbreez** is an acronym, composed of **Ta** for tantalum, **nb** for niobium, **ree** for REE, and **z** for Zr, zirconium.

These are the metals that are intended to be mined from the deposit (Tanbreez 2014, 2015).

#### 2.4.4.3 Motzfeldt REE Deposit

The Motzfeldt Centre within the Igaliko complex can be found some 60 km to the north-east of the Ilímaussaq complex. It has an age of 1273 Ma, and is rather similar to Ilímaussaq, in consisting of agpaitic rock sequences. A zone of pegmatites and hydrothermal alteration created a mineralized zone which was in the past intensively explored for assessing possible Nb-Ta-mineralisation. In 2012 re-evaluation started concerning its REE potential (Steenfelt 2012).

The rock units of the Motzfeld deposit are highly variable in texture and mineralogy, and contain very high concentrations of Th, U, Nb, Ta, Zr and REE and volatile components such as F and H<sub>2</sub>O. The inferred roof zone is the most extreme in diversity of rock types and enrichment of the elements mentioned above (Finch et al. 2001; Tukiainen 2014).

#### 2.4.5 Pilanesberg, South Africa

The Pilanesberg (also called Pilansberg) is an agpaitic ring intrusion along a contact between granitic and noritic units of the Bushveld Complex, South Africa. The Pilanesberg complex dates from the Mid-Proterozoic (approximately  $1250 \pm 50$  Ma ago). The complex is made up of phonolitic to trachitic pyroclastic rocks and lavas. These are intruded by diverse nepheline syenites, tinguaites<sup>9</sup> dikes and large cone sheets. It occurs along the noritic and granitic phases of the Bushveld complex (Ribeiro Olivo and Williams-Jones 1999). The Pilanesberg is located some 120 km NW of Pretoria. Presently it is a National Park and Game Reserve. See Fig. 2.10.

One of the major rock types, called the “green syenite”, consists of almost 20 % eudialyte, which is the main REE-carrier in the rock (Ribeiro Olivo and Williams-Jones 1999).

#### 2.4.6 Steenkampskraal, South Africa

The Steenkampskraal mine is located about 350 km north of Cape Town (see Fig. 2.11) in the Northern Cape province. The mine was first operated for thorium and also for REE by a subsidiary company of Anglo American from 1952 to 1963.

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<sup>9</sup>Tinguaites is the dike equivalent of phonolite.



**Fig. 2.10** The location of the Pilanesberg deposit, South Africa. Point of *orange balloon* is at the location of the Pilanesberg. Modified after Google Maps (2015)



**Fig. 2.11** The location of the Steenkampskraal deposit. Modified after Google Maps (2015)

**Table 2.9** REE-composition of material from the mine

Element	wt%
Y <sub>2</sub> O <sub>3</sub>	0.91
La <sub>2</sub> O <sub>3</sub>	4.78
CeO <sub>2</sub>	10.5
Pr <sub>6</sub> O <sub>11</sub>	1.18
Nd <sub>2</sub> O <sub>3</sub>	4.1
Sm <sub>2</sub> O <sub>3</sub>	0.643
Eu <sub>2</sub> O <sub>3</sub>	0.014
Gd <sub>2</sub> O <sub>3</sub>	0.436
Tb <sub>4</sub> O <sub>7</sub>	0.052
Dy <sub>2</sub> O <sub>3</sub>	0.221
Er <sub>2</sub> O <sub>3</sub>	0.065
Tm <sub>2</sub> O <sub>3</sub>	0.006
Yb <sub>2</sub> O <sub>3</sub>	0.025
Lu <sub>2</sub> O <sub>3</sub>	0.003
Total	22.935

The mine was closed in 1963, but has been re-opened because it provides an important REE source (Andreoli et al. 1994).

The current operator of the mine is Steenkampskraal Monazite Mine (Pty) Ltd. (SMM), which is 75 % owned by Rare Earth Extraction Company (“Rareco”). This company is fully owned by the Great Western Minerals Group.

The Steenkampskraal monazite district is located within the southern part of the Namaqua-Natal Metamorphic province. The age of this area is Middle Proterozoic. The largest town is Springbok.

Mineralization occurs in an ore vein, which is predominantly composed of monazite, with small amounts of allanite, REE-bearing xenotime, apatite and thorite. Mineralized material consists mainly of monazite enriched by cerium and lanthanum, but all rare earth elements are present, including yttrium. The average composition of the rocks is 45 wt% REE-oxides, 4 wt% ThO<sub>2</sub>, 18 wt% P<sub>2</sub>O<sub>5</sub>, 1 wt % Cu, 0.1–1.5 wt% ZrO<sub>2</sub>. U<sub>3</sub>O<sub>8</sub> occurs up to 600 ppm. Traces of gold are also present.

The REE composition of material from the mine (Jones and Hancox 2012) is given in Table 2.9.

### 2.4.7 Hoidas Lake, Canada

The deposit is located in the southern part of the Rae province in northern Saskatchewan, Canada (Fig. 2.12). The Rae province also hosts the uranium deposits of the Athabasca basin. The age of the mineralization is reported to be approximately 1.87 Ga (Halpin 2010).



**Fig. 2.12** The location of Hoidas Lake, Saskatchewan, Canada. Modified after Google Maps (2015)

The Hoidas Lake REE deposit is a branching and reuniting system of veins in granitic to tonalitic intrusive rocks. Apatite and allanite carry most of the REE, and only minor amounts of monazite and bastnaesite are present. The main REEs present are La, Ce, Pr, and Nd, with minor Sm and trace Dy. The grade of the deposit is reported to between 2 and 4 % total REE (Halpin 2010).

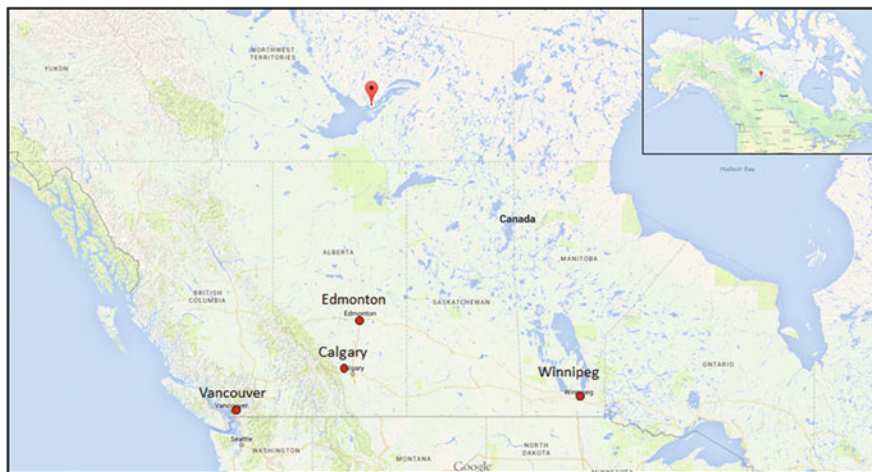
Concerning the origin of the mineralizations there are different hypotheses, which are summarized by Halpin (2010). It is suggested, that they are related to alkaline or carbonatitic magma.

Exploitation of the Hoidas Lake deposit is planned by the Great Western Minerals Group.

### 2.4.8 Thor Lake

Thor lake is located in the Northwest Territories of Canada, situated 5 km north of the Hearne Channel of the Great Slave Lake, and approximately 100 km east-southeast of Yellowknife. The location is given in Fig. 2.13 (Avalon Rare Metals 2015a).

The Nechalacho deposit (Thor Lake) is located at the Southern Margin of the Archaean Slave Province of the Canadian Shield. It is centered within the Blachford Igneous Complex, which consists of rocks of an early suite of gabbro, quartz syenite and granite, and a later suite of granite, with a core of syenite (Thor Lake syenite). The early suite is relatively aluminous, whereas the rocks of the later suite



**Fig. 2.13** The location of Thor Lake, NWT, Canada. Modified after Google maps (2015)

are of alkaline nature. These rocks also are prominently rich in Nb, REEs, F and partly in Be and Li (Cerny and Trueman 1985).

Avalon Rare Metals Inc., which owns the Nechalacho deposit, has completed a feasibility study on the deposit, which appears to be enriched in the heavy rare earths (HREEs) (Avalon Rare Metals 2015b, c).

The estimated measured mineral resources in the base case now stand at 12.56 million tons averaging 1.71 % TREO,<sup>10</sup> 0.38 % HREO and 22.5 % HREO/TREO (Avalon Rare Metals 2015c).

## 2.4.9 Strange Lake and Misery Lake

### 2.4.9.1 Strange Lake

The Strange Lake complex (a.k.a. the Lac Brisson complex), on the border of Quebec and Labrador, Canada, is a peralkaline granite which intruded metamorphic rocks and quartz monzonite. It occurs 250 km northeast of Schefferville, Quebec, and 150 km west of Nain, Labrador. The emplacement age of the earliest intrusion is approximately  $1240 \pm 2$  Ma (Miller et al. 1997). The location is given in Fig. 2.14.

The complex consists of three main units, of which the last has rare metal mineralization (Miller et al. 1997). These authors mention that the complex is similar in age, tectonic setting, spatial association (through plate reconstruction) and chemistry to rocks of the Gardar Province in South Greenland (Ilímaussaq, see

<sup>10</sup>TREO = Total Rare Earth Oxide, HREO = Heavy Rare Earth Oxide.





**Fig. 2.14** The location of Strange Lake and Misery Lake. Modified after Google Maps (2015)

2.4.4). The average composition of the ore from Strange Lake is given in Table 2.10 (Quest Rare Minerals 2014).

The deposit will be exploited by Quest Rare Minerals, Ltd.

### 2.4.9.2 Misery Lake

The Misery Lake deposit (Fig. 2.14) was discovered by Quest Rare Minerals Ltd. in 2007 during reconnaissance sampling of an unusual regional magnetic feature (Google Maps 2015). Analyses of bedrock samples gave concentrations of 27 %  $\text{Fe}_2\text{O}_3$ , 1.2 %  $\text{P}_2\text{O}_5$ , 1.5 %  $\text{TiO}_2$  and 2.25 % total REE-oxide. Further investigations in 2009 revealed a large REE-bearing alkaline intrusive complex. Misery Lake is located 120 km south of the Strange Lake deposit. It covers a total area of 44,856 ha (Quest Rare Minerals 2014). The intrusion is geologically and geochemically similar to that of Strange Lake.

**Table 2.10** Average composition of the ore from Strange Lake (Quest Rare Minerals 2014)

	Enriched zone	Granite domain
Resource	20,020 tons	258,108 tons
Composition	%	%
La <sub>2</sub> O <sub>3</sub>	0.150	0.120
CeO <sub>2</sub>	0.360	0.270
Pr <sub>6</sub> O <sub>11</sub>	0.039	0.030
Nd <sub>2</sub> O <sub>3</sub>	0.140	0.110
Sm <sub>2</sub> O <sub>3</sub>	0.036	0.024
Eu <sub>2</sub> O <sub>3</sub>	0.002	0.001
Gd <sub>2</sub> O <sub>3</sub>	0.039	0.023
Tb <sub>4</sub> O <sub>7</sub>	0.009	0.005
Dy <sub>2</sub> O <sub>3</sub>	0.066	0.032
Ho <sub>2</sub> O <sub>3</sub>	0.015	0.007
Er <sub>2</sub> O <sub>3</sub>	0.049	0.022
Tm <sub>2</sub> O <sub>3</sub>	0.008	0.003
Yb <sub>2</sub> O <sub>3</sub>	0.051	0.022
Lu <sub>2</sub> O <sub>3</sub>	0.007	0.003
Y <sub>2</sub> O <sub>3</sub>	0.470	0.220
Total	1.018	0.451



**Fig. 2.15** The location of the Nolans Bore deposit, Northern Territory, Australia. Modified after Google Maps (2015)



### 2.4.10 *Nolans Bore Deposit, Australia*

The Nolans Bore deposit (Arunta Region, NT) is located in a zone which also contains the Mud Tank Carbonatite, Mordor Igneous Complex, and several tin- and tantalum-bearing pegmatites (Fig. 2.15). The deposit was discovered in 1995 (Arafura Resources 2014).

The Nolans Bore mineral field of carbonatites, pegmatites, and other REE occurrences consist of mineralized fluorapatite veins and breccia zones, which are hosted in majority by granite (metamorphosed to gneiss).

The granite-gneiss has been strongly kaolinized due to weathering. The weathering zone shows secondary enrichment of REE. The average REE-composition is given in Table 2.11.



**Fig. 2.16** The location of the Norra Kärr deposit. Modified after Google Maps (2015)

**Table 2.11** Average REE-composition of the Nolans Bore deposit (Arafura Resources)

Element	% of total REO
La	19.1
Ce	48.7
Pr	5.9
Nd	20.6
Sm	2.3
Eu	0.39
Gd	0.99
Tb	0.08
Dy	0.32
Y	1.35
Other	0.21

### 2.4.11 Norra Kärr, Sweden

The Norra Kärr alkaline igneous complex is located in southern Sweden, in the province of Småland, about 1.5 km east of Lake Vättern and about 15 km NNE of the small town of Gränna (Fig. 2.16). Discovered by A. E. Törnebohm in 1906 (Törnebohm 1906), the complex was studied in detail by von Eckermann (1968). The intrusion is roughly elliptical in shape (1200 m × 400 m). The age of the intrusion is  $1489 \pm 8$  Ma (Sjöqvist et al. 2013). The deposit is exploited by Tasman Metals Ltd, and it is especially enriched in the HREEs, which make out more than 50 % of the total REE content (Tasman Metals 2014b). The main ore mineral is eudialyte.

### 2.4.12 Lovozero and Khibina Massifs, Kola Peninsula, Russia

The Kola alkaline province occupies the Kola Peninsula, northern Karelia and the adjoining regions of Northern Finland. Two large agpaitic intrusions are the key magmatic centers. The Khibina<sup>11</sup> massif consists of intercalations of K–Na and K nepheline syenites with typical ultrabasic-alkaline and carbonatitic rocks. In the Lovozero massif, there are agpaitic lujavrites<sup>12</sup> (type locality), which form a layered complex similar to Ilímaussaq, Greenland. Geochronological data show the age to be Paleozoic (Arzamastsev et al. 2008).

The larger of the two agpaitic nepheline syenite intrusions is that at Khibina, with an exposed surface of 1327 km<sup>2</sup>. Close by there is a second agpaitic complex with an exposed surface of 650 km<sup>2</sup>, the Lovozero intrusion (Fig. 2.17). It is located

<sup>11</sup>Khibina is also spelled as Khibiny, or Khibini.

<sup>12</sup>The name Lujavrite is derived from the Saami-word Lujávri, meaning (Lake) Lovozero.



**Fig. 2.17** Location of the Lovozero and Khibiny intrusions. Modified after Google maps (2015)

about 20 km north east of Khibina. Both alkaline complexes include apatite and loparite deposits which are of economic importance.

Apatite from the Khibina alkaline complex is mainly fluorapatite  $\text{Ca}_5(\text{PO}_4)\text{F}$ , with enrichment of light rare earth elements (La, Ce, Pr, Nd, Sm, Eu). The investigated LREE + Y contents range from 4268 to 4464 ppm (with an average of 656 ppm for Nd). The content of the more rare heavy rare earth elements (Gd, Dy, Er, Yb) is minor (HREE = 405 ppm). (Stoltz and Meyer 2012).

#### **2.4.13 Nkwombwa Hill Carbonatite Deposit, Zambia, and Other East- and Middle-African REE-Deposits**

Although there is more than one deposit in Central Africa, the most important at the moment is the Nkwombwa Hill Carbonatite Deposit, Zambia (Turner et al. 1989). Originally mapped as a limestone deposit, it was later recognised as a carbonatite plug (Zambezi et al. 1997). The carbonatite plug is elliptical in form, measuring some  $600 \times 1200$  m and some 300 m in height. The age was determined at  $679 \pm 25$  Ma (Snelling 1965), which is Neoproterozoic.



**Fig. 2.18** Nkwombwa Hill in NE Zambia. Modified after Google Maps (2015) and Zambezi et al. (1997)

Emplacement is thought to have been controlled by a major NE–SW trending fault. The sills and dykes of ferrocarnatite contain irregularly distributed angular xenoliths, typically 10 cm or more in size, which locally make up some 20–25 % by volume of the rock.

Rare earth mineralization at Nkwomba Hill is restricted to these xenoliths (Zambezi et al. 1997). The average composition of the xenoliths is given in Table 2.12. The REEs are largely LREEs. The high-grade rare earth mineralization will be exploited by Galileo Resources Plc, a 2005 founded, UK registered company.

Other carbonatite-related REE-deposits in Central and East Africa are, for instance:

- The Kangankunde Carbonatite Complex, Malawi. This is one of several carbonatite complexes in southern Malawi associated with the Shire Valley section of the East African Rift System. The Kangankunde Carbonatite Complex differs significantly from other carbonatite in the marked absence of nepheline syenite and other silicate rocks like lamprophyres and melanephelinite (Duraiswami and Shaikh 2014). Main REE-minerals are monazite-Ce and bastnaesite-Ce, and to a lesser extent florencite-goyazite<sup>13</sup> (Wall and Mariano 1996). Resources at the

<sup>13</sup>Goyazite is:  $\text{SrAl}_3(\text{PO}_4)_2(\text{OH})_5$

Florencite is:  $(\text{Ce, La})\text{Al}_3(\text{PO}_4)_2(\text{OH})_6$

**Table 2.12** Average composition of REE-rich xenoliths from Nkwombwa Hill, Zambia (Zambezi et al. 1997)

	wt%
SiO <sub>2</sub>	0.52
Fe <sub>2</sub> O <sub>3</sub>	1.09
La <sub>2</sub> O <sub>3</sub>	8.25
Ce <sub>2</sub> O <sub>3</sub>	15.35
Pr <sub>6</sub> O <sub>11</sub>	1.25
Nd <sub>2</sub> O <sub>3</sub>	1.76
Sm <sub>2</sub> O <sub>3</sub>	0.15
Eu <sub>2</sub> O <sub>3</sub>	0.12
Gd <sub>2</sub> O <sub>3</sub>	0.26
SrO	1.95
BaO	12.28
MnO	0.58
CaO	15.65
MgO	7.70
P <sub>2</sub> O <sub>5</sub>	1.27
LOI	28.10
Total	96.30

Kangankunde deposit are estimated to be 2.53 Mt at a grade of 4.24 % rare earth minerals (Yager 2011).

- The Tundulu Complex, Malawi, is a carbonatite with veins with mainly LREE mineralization. The REE-minerals are synchysite, parisite, and bastnaesite (Ngwenya 1994).
- The Songwe Hill Rare Earth Element (REE) Project, which will be exploited by Mkango Resources Ltd., is located within the 100 %-owned Phalombe License, which covers a portion of the Cretaceous Chilwa Alkaline Province in Southern Malawi (Mkango Resources Ltd 2014).

#### 2.4.14 Maoniuping, Sichuan, China

In Sichuan, China, the Maoniuping Deposit is the second largest LREE deposit in China (Fig. 2.19). It occurs in the northern Jinpingshan Mountains, a Cenozoic intracontinental orogenic belt.

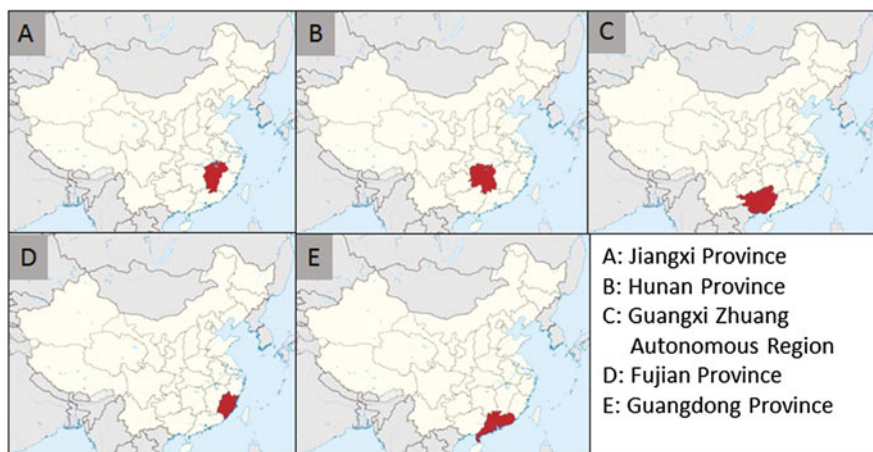
It is a vein type deposit, which is hosted within, and is genetically related to, a carbonatitic alkaline complex. The deposit is very similar to the Californian Mountain Pass deposit. The similarities are the high concentrations of bastnaesite and barite, low niobium content, and the presence of sulphides (Wang et al. 2001). It has proven reserves of 0.4 million tons of ore grading at 2 % REE oxides. The discovery of the deposit was described by Pu (1988). The age of the carbonatites related to the deposit is 27.8–40.3 Ma (Cheng et al. 2003; Mindat.Org 2015).

**Fig. 2.19** Location of the Maoniuping REE deposit, Sichuan, China. Modified after Wikipedia



#### 2.4.15 Chinese Ion Adsorption Deposits

China's weathered-crust elution-deposit rare earth ore, called ion-adsorption rare earth ore, is unique. This type of ore was discovered in 1969 in the Jiangxi Province. There are two types of deposits: light REE type (A) and heavy REE type (B). It was found also in other Chinese provinces: Fujian, Hunan, Guangdong, and Guanxi. The provinces where these deposits are found are given in Fig. 2.20. The



**Fig. 2.20** The provinces of China where the Ion Adsorption Ores have been found. Image composed and modified after Wikipedia

**Table 2.13** Average compositions of two types of REE ion adsorption ores from China (Zhi Li and Yang 2014)

Oxide	wt%	wt%
	Type A	Type B
La <sub>2</sub> O <sub>3</sub>	31–40	2–5
CeO <sub>2</sub>	3–7	1–5
Pr <sub>6</sub> O <sub>11</sub>	7–11	1–2
Nd <sub>2</sub> O <sub>3</sub>	26–35	3–5
Sm <sub>2</sub> O <sub>3</sub>	4–6	2–4
Eu <sub>2</sub> O <sub>3</sub>	0.5	0.12
Gd <sub>2</sub> O <sub>3</sub>	4	6
(Tb–Lu) <sub>2</sub> O <sub>3</sub>	4–5	15–20
Y <sub>2</sub> O <sub>3</sub>	9–11	>60

deposits are considered to have formed by weathering of granite and effusive rocks over many years. REEs are in the form of positive hydrated ions, adsorbed on the surface of clay minerals like kaolinite, halloysite and illite. The ores are relatively low grade, generally 0.05–0.5 % REO, but with high amounts of HREE (Zhi Li and Yang 2014). See Table 2.13 for average compositions. The known reserve of these ore deposits is more than  $1 \times 10^6$  tons REO (rare earth oxide). The known reserve of HREE in China is 80 % of the total world reserve of REE (Zhi Li and Yang 2014).

### 2.4.16 Dong Pao, Vietnam

In the north-western part of the Lai Châu Province, in the Tam Duong district of Vietnam, a major rare earth element deposit occurs (Fig. 2.21). This deposit, called Dong Pao, consists of irregular shapes with nests, lenses and veins in a shear zone of limestone that was hydrothermally altered. Mineralization consists of bastnaesite, fluor spar and parisite as the main ore minerals. The deposits in the Nam Xe area are similar to the Dong Pao deposit (Fong Sam 2011).

The Dong Pao Rare Earth mine covers a total area of 11 square miles, and has estimated reserves of 5 million tons (Fong Sam 2011).

The Dong Pao Mine is jointly operated by Lai Chau-VIMICO Rare Earth Joint Stock Co. and the Japanese Dong Pao Rare Earth Development Company (Talk Vietnam 2012).





**Fig. 2.21** Location of the Dong Pao Rare Earth Deposit, Vietnam. After Google Maps (2015), and Wikipedia (2015a–f)



## 2.5 Resources in the Deep Sea

In recent years more and more research has been conducted to locate ore deposits in the deep sea. Although not exclusively a target, REEs have also been found in deep sea deposits. The origin of the REE may be diverse: rivers, aeolian processes and hydrothermal processes (de Baar et al. 1985; Ederfeld and Greaves 1982).

### 2.5.1 *Pelagic Muds*

Kato et al. (2011) found vast amounts of deep sea mud in the Pacific Ocean. The muds are generally metalliferous sediment, zeolitic clay, and pelagic<sup>14</sup> red clay. Thicknesses vary from a few meters to 70 m. They occur up to 50 m below the sea floor. These deposits occur in the eastern South Pacific and central North Pacific. They contain 1000–2300 ppm total REY (REE + Y). In the eastern South Pacific (5°–20° S, 90°–150° W), the REY-rich mud has high REY contents, 1000–2230 ppm total REY and 200–430 ppm total HREE. REY contents of the mud are comparable to or greater than those of the southern China ion-absorption-type deposits (where  $\Sigma\text{REY} = 500\text{--}2000$  ppm;  $\Sigma\text{HREE} = 50\text{--}200$  ppm); notably, the HREEs are in general nearly twice as abundant as in the Chinese deposits (Kato et al. 2011).

### 2.5.2 *Crusts on Seamounts*

Seamounts may have a diverse origin. In general, any conical or steep volcanic feature at the sea floor is referred to as a seamount, and these may be, or may not be, volcanically active. Seamounts occur in groups or in chains. They originate from different eras, and are mostly found at convergent plate boundaries and in areas of vertical tectonic movement. They also occur at intersections of ridge faults<sup>15</sup> and transform faults,<sup>16</sup> at spreading centers and at hotspots. Seamounts range from small domes of tens of meters to large structures of several kilometers in height. Commonly, they have steep outer slopes, flat or nearly flat circular summit areas

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<sup>14</sup>Pelagic red clay: red colored fine-grained sediment that accumulates as the result of the settling of particles to the floor of the open ocean, far from land. The color results from coatings of iron oxide and manganese oxide on the sediment particles (Source Wikipedia (2015a) Pelagic Red Clay). The word “pelagic” comes from the Greek, and means “open sea”.

<sup>15</sup>Ridge faults are central faults from mid-oceanic ridges, which are huge submarine mountain chains.

<sup>16</sup>Transform faults are also known as conservative plate boundaries, as they neither create nor destroy lithosphere. These faults have a relative motion which is predominantly horizontal. They tend to be approximately at right angles to mid-oceanic ridges.

and collapse features (calderas, pits, craters). Metal deposits are usually found on the slopes and flanks of the seamounts.

Cerium was reported among others by Baturin and Yushina (2007). In a publication from 2008, the ISA confirmed the occurrence of cobalt-rich crusts (ISA, 2008).

### 2.5.3 *Exploitation of Deep-Sea Deposits*

The main problem with exploitation of deep-sea deposits is their depth: they tend to occur in water which is several kilometers deep. It is evident that this entails substantial technical difficulties. The exploitation of these deposits, outside the Exclusive Economic Zone (EEZ) of coastal and island states (200 miles offshore) is under the supervision of the International Seabed Authority (ISA 2015).

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