Delft University of Technology
Department of Geosciences and Engineering

Bachelor Thesis in Applied Earth Sciences

Rare Earth Element Deposits and Occurrences within Brazil and India

Indicating and describing the main REE deposits & occurrences and their potentialities

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By
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ABSTRACT

The aim of this thesis is to describe the rare earth element (REE) occurrences, reserves and resources in Brazil and India and to investigate future potentiality of these deposits and any other potential REE resources in South America. This report is completely based on literature studies, no experiments or fieldwork were carried out. Firstly, this thesis starts off with an introduction on what the REEs are, in which form they occur and why they are essential in today's society. Also the topic of why Brazil and India are chosen as countries for this study will be covered. Afterwards the main REE-carrying mineral deposits within Brazil (and India as well) are described. These deposits are mainly carbonatites, granitic deposits and (mostly shoreline) placer deposits. Estimated resources and reserves are given per location, along with other information of the deposit. Information like: age, REE content and grade, other valuable mineral content and the feasibility and future potentiality of the deposits. Furthermore, a link will be made between some of the described (granitic) deposits within Brazil and potentially other resources in South America. For India, the main mineral deposits are described in the same manner as for Brazil. However, for the sake of the length of this report the descriptions are limited to the currently operating Indian Rare Earths Limited (IREL) plants. For India, as well as for Brazil, more (less significant) deposits are briefly displayed in the Appendices found at the end of the report.

PREFACE

Herewith I present my Bachelor Thesis that was written in partial fulfilment of the requirements of degree Bachelor of Science in Applied Earth Sciences. This thesis came to be as an interest in the subject of rare earth elements and its applications, which was offered to me during a presentational lecture given by Dr. J.H.L. Voncken on the occasion of the publication of his new book 'The Rare Earth Elements: An Introduction' (ISBN 978-3-319-26807-1).

Dr. Voncken offered me the opportunity to elaborate on his recent publication in the form of describing the rare earth element deposits and occurrences within Brazil and India, wherefore I wish to thank him. I would also like to thank him and Dr. A. Barnhoorn for being my supervisors during this project. Special thanks go out to Dr. Voncken for being available at any moment and always willing to answer my questions and providing me with feedback and support during the last eight weeks.

D. Louwerse
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1

INTRODUCTION

1.1. General Introduction

For my Bachelor project I had the opportunity to write a thesis on a recently very popular and evolving subject. It is a complement to the book of Dr. J.H.L. Voncken: ‘The Rare Elements: An Introduction’. I have been doing a study indicating and investigating the rare earth element (REE) occurrences in Brazil and India. This chapter will start with a short introduction on what the REEs are and in what form they occur. After that, the recent interest and importance of these REEs and this study will be covered.

1.1.1 The Rare Earth Elements

The REEs are a group of 17 heavy elements (Scandium, Yttrium and the Lanthanide group) which belong to the Transition Metals, group 3b of the Periodic Table of Elements. These REEs are subdivided into light- and heavy-REE’s (LREE and HREE).

Light REE	**Heavy REE**
Scandium (Sc)	Yttrium (Y)
Lanthanum (La)	Terbium (Tb)
Cerium (Ce)	Dysprosium (Dy)
Praseodymium (Pr)	Holmium (Ho)
Neodymium (Nd)	Erbium (Er)
Promethium (Pm)	Thulium (Tm)
Samarium (Sm)	Ytterbium (Yb)
Europium (Eu)	Lutetium (Lu)
Gadolinium (Gd)	

1.1.2 The REE Carrying Minerals

These Elements are carried by ore minerals. The major REE bearing ore minerals are Monazite, bastnaesite, xenotime and eudialyte. Table 1.1, 1.2 and 1.3 are showing the major- and minor REE carrying minerals.

Within monazite ($CePO_4$), one can find (as the chemical formula shows) the mineral Cerium, but also other REE are occurring in monazite. These are mostly the LREEs: La, Pr, Nd and Sm (Voncken, 2016). Monazite occurs generally as a minor mineral in granites, granodiorites, and associated pegmatites and in many metamorphic rocks. Monazite is very resistant to weathering, so it concentrates after weathering of the igneous or metamorphic host rock and subsequent transport in placers and heavy mineral sands (Gupta and Krishnamurthy, 2005). Monazite often contains the radioactive element thorium. A large disadvantage of processing this radioactive material is that the disposal of radioactive waste causes more expenditures and social concern. This will be further discussed later on.

Bastnaesite ($Ce(CO_3)F$) also carries mainly the LREEs of Ce, La, Pr and Nd. For the HREEs, only Yttrium is regularly found in this mineral, but low proportions of other HREEs are also present. The chemical formula again shows Cerium, but the added prefix is dependent on the dominant REE, and could be Ce as well as La, Nd or Y (Voncken, 2016). Bastnaesite is occurring worldwide, but it never in large quantities. Bastnaesite has been found in a variety of igneous rocks, such as carbonatites, vein deposits, contact metamorphic rocks and pegmatites (Gupta and Krishnamurthy, 2005). The largest ore deposits are generally related to carbonatite intrusions as the deposits, indicated in report will point out. These carbonatites are often found in relation to alkaline intrusives.

Xenotime (generalized formula: YPO_4) carries, in contrast to monazite and bastnaesite, other than Y, also a substantial amount of HREE. Xenotime may contain up to 67% of rare earth oxides (REO), with mostly the heavier elements (Gupta and Krishnamurty, 2005). The most often occurring elements within xenotime are Dy, Yb, Er and Gd. It also contains lesser concentrations of Tb, Ho, Tm and Lu. Xenotime is the biggest source for HREE. Xenotime occurs in small quantities within pegmatites and other (non-basic) igneous rocks, but is also common in metamorphic rocks (Voncken, 2016). Monazite and xenotime are quite alike when it comes to specific gravity (in the range of 4.4-5.1) and therefore, xenotime, just as monazite, tends to concentrate in placers and heavy minerals sands, although these deposits are not widely spread (Gupta and Krishnamurthy, 2005). Xenotime has in addition to monazite, which carries mostly thorium, often uranium as major actinide group. The disadvantage in this could be that processing xenotime can be a lot more expensive due to the removal and disposal of radioactive waste. An interesting case in this matter is the Mt. Weld deposit, which is owned by Lynas Corporation. Lynas exported their ore to Malaysia for processing. However the radioactive waste (radioactive thorium and uranium) coming from processing xenotime could not be shipped back to Australia for safe disposal, since Australian authorities have explicitly refused to accept them (Lynas Corporation, 2011). This is how Malaysia got stuck with the waste and is a good example of the problems and excessive costs which may occur with processing xenotime.

Table 1.1: *Examples of typical monazite, xenotime and bastnaesite compositions (Voncken, 2016).*

Element	Monazite-Ce	Monazite-La	Xenotime-Y
La_2O_3	16.95	33.95	–
Ce_2O_3	34.16	17.10	–
ThO_2	5.50	5.50	–
P_2O_5	29.55	29.58	38.60
Nd_2O_3	14.01	14.03	–
Y_2O_3	–	–	61.40
CO_2	–	–	–
F	–	–	–
$O = F_2$	–	–	–
Total	100.17	100.17	100.00
Element	Bastnaesite-Ce	Bastnaesite-La	Bastnaesite-Y
La_2O_3	–	74.76	
Ce_2O_3	74.90	–	
ThO_2	–	–	
P_2O_5	–	–	
Nd_2O_4	–	–	
Y_2O_3	–	–	67.24
CO_2	20.08	20.20	26.21
F	8.67	8.72	11.31
$O = F_2$	−3.65	−3.67	−4.76
Total	100.00	100.00	100.00

Eudialyte is a cyclosilicate with the general formula $Na_4(Ca, Ce)_2(Fe^{2+}, Mn^{2+})ZrSi_8O_{22}(OH, Cl)_2$. The name Eudialyte means readily decomposable in Greek, which refers to its easy solubility in acids (Handbook of Mineralogy, 2001). Igneous Eudialyte occurs within undersaturated alkaline intrusions and associated pegmatites (Deer et al, 1986).

Table 1.2: *Two typical compositions of Eudialyte (Voncken et al., 2016).*

Element	Kipawa Lake, Canada wt%	Khibiny Massif, Russia wt%
SiO_2	50.35	50.14
TiO_2	0.38	0.46
ZrO_2	11.80	11.83
Al_2O_3	0.44	0.07
RE_2O_3	6.40	0.37
Fe_2O_3	0.19	0.50
Nb_2O_5	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_2O	12.53	14.06
K_2O	0.43	1.39
F	0.23	
Cl	1.47	1.82
H_2O^+	1.64	1.07
H_2O^-		0.12
P_2O_5	0.03	
S		0.04
$-O = (F, Cl)_2$	0.43	0.41
Total	99.88	99.38

There are a lot more REE-bearing minerals, but usually they are not carrying enough for industrial extraction. The LRE elements can also replace for one another in these minor REE-bearing minerals, just as in the major REE-bearing minerals. Table 1.3 below shows the minor REE-bearing minerals known up to now (Voncken, 2016).

Table 1.3: *Minor REE-bearing minerals (Voncken, 2016).*

Mineral name	Formula
Aeschynite	$(Ce, Ca, Fe)(Ti, Nb)_2(O, OH)_6)$
Aenigmatite	$(Na, Ca)_4(Fe, Ti, Mg)_{12}Si_{12}O_{40}$
Allanite (Orthite)	$(Ca, Ce)(Al, Fe^{2+})(Si_2O_7)(SiO_4)O(OH)$
Ancylite	$SrCe(CO_3)_2(OH)\cdot(H_2O)$
Apatite	$Ca_5(PO_4)_3F$ Apatite is as such not a rare earth mineral, but REEs may concentrate them, in which case they substitute for Ca
Brannerite	$(U, Ca, Ce)(Ti, Fe)_2O_6$
Britholite	$Ca_2(Ce, Ca)_3(SiO_4, PO_4)_3(OH, F)$
Cerite	$(Ce, La, Ca)_9(Mg, Fe)(SiO_4)_3(HSiO_4)_4(OH)_3$
Cerianite	$(Ce, Th)O_2$
Cheralite	$(Ca, Ce)(Th, Ce)(PO_4)_2$
Churchite	$YPO_4\cdot 2(H_2O)$
Euxenite	$(Y, Ce, Ca)(Nb, Ta, Ti)_2O_6$
Fergusonite	$Y(Nb, Ti)O_4)$
Florencite	$(Ce, La)Al_3(PO_4)_2(OH)_6$
Gadolinite	$Y_2Fe^{2+}Be_2Si_2O_{10}$
Huanghoite	$BaCe(CO_3)_2F$
Hydroxylbastnaesite	$(Ce, La, Nd)CO_3(F, OH)$
Kainosite	$Ce_2(Y, Ce)_2(Si_4O_{12})(CO_3)\cdot H_2O$
Loparite	$(Na, Ce, Ca, Sr, Th)(Ti, Nb, Fe)O_3$
Mosandrite	$Na(Na, Ca)_2(Ca, Ce, Y)_4(Ti, Nb, Zr)(Si_2O_7)_2(O, F)_2F_3$
Parisite	$Ca(Ce, La)_2(CO_3)_3F_2$
Rinkite	$(Na, Ca)_3(Ca, Ce)_4Ti(Si_2O_7)_2OF_3$
Samarskite	$(Y, Fe^{3+}, U) (Nb, Ta)_5O_4$
Synchisite	$Ca(Ce, Nd, Y)CO_3F$
Steenstrupine	$Na_{14}Ce_6Mn^{2+}Mn^{3+}Fe_2^{2+}(Zr, Th)(Si_6O_{18})_2(PO_4)_7\cdot 3(H_2O)$
Tengerite	$Y_2(CO_3)_3\cdot 2\text{–}3(H_2O)$
Thalenite	$Y_3Si_3O_{10}(OH)$
Yttrotantalite	$(Y, U, Fe)(Ta, Nb)O_4$
Zircon	$ZrSiO_4$. Zircon also is not a rare earth mineral as such, but like apatite, it may concentrate REEs, in which case they substitute for Zr

1.2 The Importance of REEs

The Rare Earth Elements were until 1948 mostly sourced from placer sand deposits within India and Brazil (Rose, 1960). Within the 1950s South Africa became the world's largest REE source, when large veins of monazite were discovered (Rose, 1960). From the 1960s to the 1980s the Mountain Pass REE mine in California, U.S. was the leading global REE producer.

Nowadays China produces 97% of the world's REE supply, which gives them almost a monopoly on the production of the REEs. This resulted in China changing its position towards the global REE market in 2009. China introduced production quotas, export quotas and taxes, enforced environmental legislation and granted no new rare earth mining licenses (Geschneider, 2001). This monopoly of China led to a global anxiety at large manufacturing companies of high tech equipment. A lot of nowadays high tech applications are not feasible without REEs. Some examples of these applications are: hard-disk drivers, smart phones, flat-screen televisions, lasers, permanent magnets and energy saving lamps. That period, starting in 2009 is now known as the 'Rare Earth Crisis' (Voncken, 2016). This made a lot of people aware about the group of elements mentioned above in chapter 1.1.

In March 2012, the US, EU and Japan confronted China in the WTO about these restrictions. China responded with claims that the restrictions were made with environmental protection in mind (Reuters, 2012). In August 2012, China announced a further 20% reduction in production (CNN, 2012). These restrictions damaged industries in other countries and forced producers of rare earth products to relocate their operations to China (Reuters, 2012). On August 29, 2014, the WTO ruled that China had broken free trade agreements, and afterwards, on September 26, 2014, China declared it would implement the ruling in their national regulations, but would need some time to do so. By January 5, 2015, China had lifted all quotas from the export of rare earths; however export licenses will still be required (The Guardian, 2015).

This offered the rest of the world some reassurance on their supply of REEs. However, bearing in mind that China still has the largest REE production (97%) worldwide (Voncken, 2016), it is important to investigate, inventory and describe the existing REE deposits in other parts of the world. Also it is important to keep exploring for new resources, as the demand of high-tech applications increases. This increase is due to the upcoming growth of secondary economies like India, which has a total of over 1.2 billion inhabitants (UN, 2011). These people would also like to participate in the western-, first world culture. This means having smartphones, electric cars, flat-screen televisions etc.

That is where the importance of this study comes in. Within Brazil and India, which have been known for producing REE in the past, are some deposits, containing REE resources which were not feasible for production up to now. Within these two developing BRIC (BRIC countries: Brazil, Russia, India, China) economies, as stated before, the demand for high-tech applications, thus, REEs increases. With China having such a strong grip on the global market, it could be potentially economically better for these countries to produce their own REE.

That is why this study was done: To indicate and describe the REE deposits in Brazil & India. The main deposits and resources will be described as elaborate as possible. Further minor occurrences and depleted resources will be briefly discussed and/or displayed in the appendix, showing all known notable REE deposits within Brazil and India, up to today.

2

Rare Earth Deposits within Brazil and India

2.1 Brazil

Within Brazil, REE concentrations have been found in all sorts of rock types, but the most economic rare earth element mineral deposits are mostly found in 3 types of occurrences. These types of occurrences can be classified as two primary sources of REEs and one secondary source of REEs. The first one, which contains the largest amount of REE within Brazil, is the primary source that can be found within carbonatites and alkaline complexes. The second primary occurrence is within granite deposits. And lastly, REE are often found occurring as secondary source within placer deposits (Takehara et al., 2014). The total proven reserves of rare earth elements in Brazil have been estimated on 22 Mt, which is around 20% of the world total (USGS, 2016). Resource estimation for REOs in Brazil points out that close to 53 Mt is present in the current known deposits (Chen, 2011). This is over 32% of the world's total REE resource, whereas China is estimated to host 22% of world's total REE resource. These estimations suggest that Brazil might surpass China and rank as first in rare earth deposits production. However, the production of REEs in Brazil is fairly low at the moment (140 tons/year in 2013) (Mining-Technology, 2014).

2.1.1. Carbonatite Deposits

Carbonatites are intrusive or extrusive igneous rocks defined by mineralogical composition consisting of greater than 50% carbonate minerals (Bell,1989). They usually occur as small plugs within zoned alkaline intrusive complexes, or as dikes, sills, breccias and veins. Carbonatites mostly exist of Na_2O, MgO and CaO plus CO_2. Calcite and dolomite are often the rock forming minerals. Most carbonatites do often include some silicate mineral fraction. Silicate minerals within these carbonatites are often pyroxene, nepheline. Additionally to this, the carbonatites may be enriched in either: magnetite, apatite, fluorine, barium and REEs (Guilbert & Park, 1986). This last enrichment is what we are looking for in our deposits. Carbonatite deposits are mostly related to LREEs and iron ore deposits. (Takehara et al., 2014). There are a lot of REE-bearing carbonatite deposits within Brazil. The largest, potentially most economic, and therefore best known deposits will be described below.

Carbonatite complexes usually form circular structures and develop radial drainage patterns (Gomes et al., 1990). This drainage system in association with tropical weathering contributes to the development of such a thick weathering profile that could reach up to more than 250 meters in depth (like the Araxá complex) (Brod et al., 2004). As mentioned before in the description of the REE-bearing minerals, the main REE-bearing minerals such as monazite and xenotime are very resistant to weathering, so they tend to concentrate after weathering of the host rock. This results for the described deposits below in notable concentrations of rare earths.

Araxá

Within the Minas Gerais near a place called Araxá, rare earth minerals occur in residual soils which are overlying the deeply weathered Barrairo do Araxá carbonatite complex. This complex is the world's largest and principal source of niobium. The complex is 87.2 ± 4.4 Ma years old, from the Coniacian, Upper Cretaceous and consists of weathered carbonatites. The complex is a circular consisting of 3 separate deposits which have a total diameter of 4,5 kilometer (Neary and Highly, 1984).
Figure 2.1.1 shows the location of the mines (CBMM & MBAC) near Araxá.

Fig. 2.1.1: *Location of the Araxá deposit. Modified after Google Maps (2016)*

REE are occurring in the form of monazite and goyazite minerals. This mine, which is owned by Companhia Brasileira de Metalurgia e Mineração (CBMM) contains more than 450 Mt Niobium ore at a grade of 2,5% Nb2O5 of which 4.4% of the ore won during the exploitation are rare earth oxides (Issa Filho et al., 1984). Additional to this resource, the complex also contains 800.000 tons of supergene-enriched laterite which has 13,5% REO in it, mainly in the form of phosphate minerals: gorceixite ($BaAl_3(PO_4)(PO_3OH)(OH)_6$) and goyazite ($SrAl_3(PO_4)_2(OH)_5 \bullet (H_2O)$) (Mariano, 1989) The total reserves have been estimated on 120.000 ton REO (McNeil, 1979). And the total resources have been estimated at 22 Mt with an average grade of 3,02% (Departamento Nacional de Produção Mineral (2013).

The project in the Araxá carbonatite complex is the most advanced production project of REEs in brazil, with a production of 100 tons/month of hydroxides and bisulfates of REEs (Revista de Audiencias Publicas do Senado Federal, 2013).

Another project which has been started up is the Araxá Rare Earth/Niobium/Phosphate project by MBAC Fertilizer Corp. (MBAC, 2013). This project is located next to the world's largest operating niobium mine from CBMM (which has been mentioned above) and a phosphate mine which is owned by Vale. Because this project is so close to the other two operating mines, the project benefits from the existing local infrastructure. In June 2012, resource estimation was done and a measured & indicated total rare earth oxides (TREO) resource was found to be 6.3Mt with a grade of 5.01% (using a 2% TREO cut-off). Also the inferred mineral resource was estimated to be 21.9Mt with an average TREO content of 3.99% (again using a 2% TREO cut-off). MBAC reports show that the MBAC Araxá project is going to have a 40 year mine life with an after-tax NPV of $967 Million with an IRR of 30% (MBAC, 2013).

The great advantage of Brazilian REE carbonatite deposits such as the Araxá deposit is that the REE mineralization is associated with other ores that are being mined. So REE can be produced as byproducts. The disadvantage of the Araxá deposit is that this deposit is very rich in LREEs but has a low concentration of HREEs, which are more critical, so potentially more valuable (Takehara et al., 2014).

Barra do Itapirapuã

The Barra do Itapirapuã deposit is a carbonatite deposit located in the province of São Paulo. This rock belongs to the final stages of the Ponta Grossa Arch Province dated from Early Cretaceous alkaline rock (Ruberti et al., 2008). Hydrothermal alteration of the carbonatite deposit has led to the formation of quartz, apatite, fluorite, barite, sulfides and rare earth carrying (fluorocarbonate) minerals, such as: bastnaesite, ancylite, synchysite and parisite (Andrade et al., 1999). The main REE carrier is bastnaesite and the total estimated resource is 44.8 Mt REE_2O_3 with a grade of 0.7% (Lapido-Loureiro, 1988).
Figure 2.1.2 shows the location of the Barra do Itapirapuã carbonatite deposit.

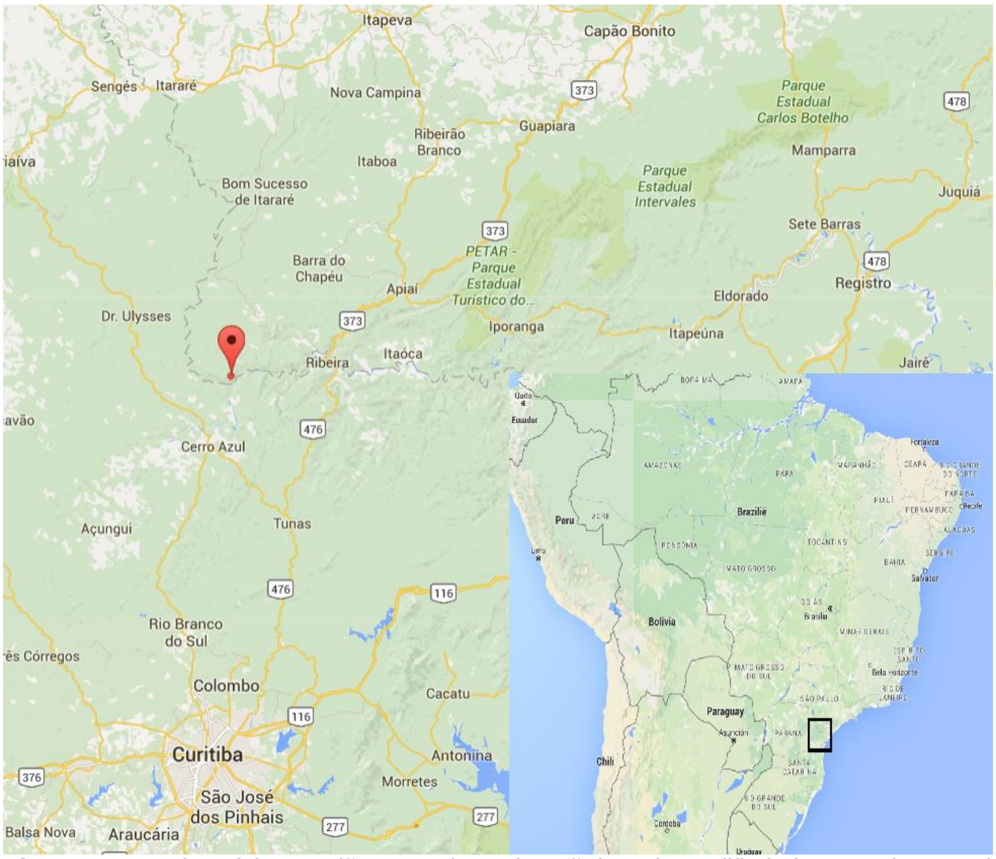

Fig. 2.1.2: *Location of the Catalão Barra do Itapirapuã deposit. Modified after Google Maps (2016)*

Catalão I
In the Province of Goiás, another carbonatite complex can be found, this is the Catalão I deposit. The deposit is approximately 82.9 ± 4.2 Ma (Upper-Cretaceous, Campanian) and is shaped in the form of a plug with a diameter of 6 kilometer (Woolley, 1987).
Figure 2.1.3 shows the location of the Catalão I deposit.

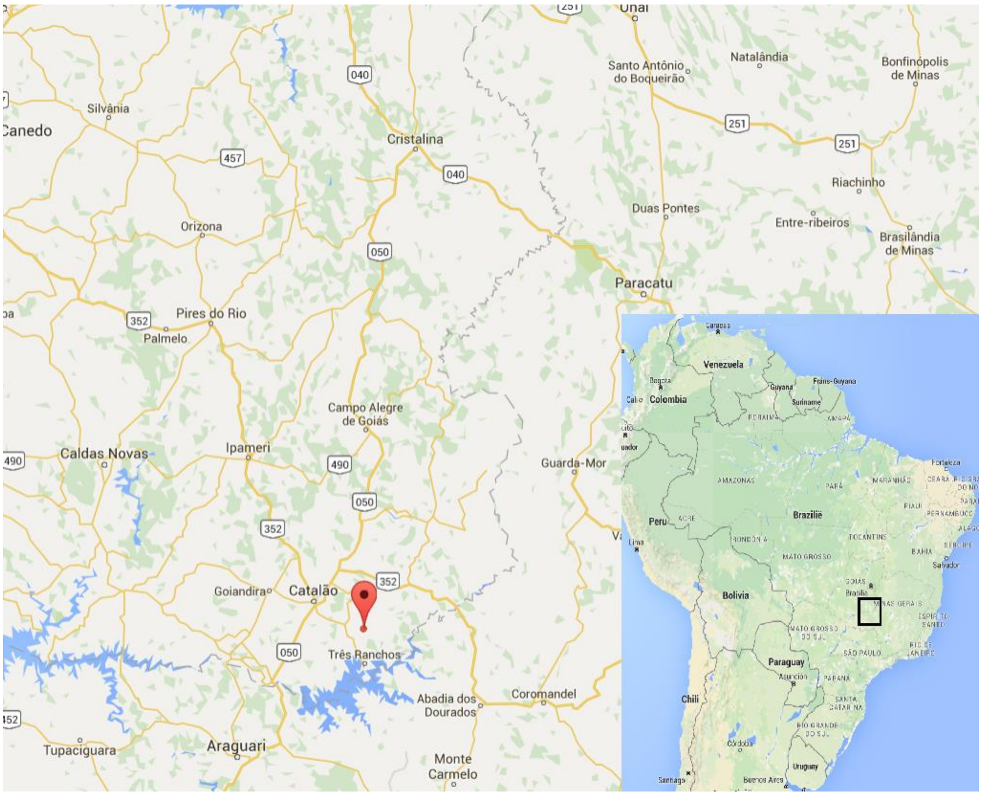

Fig. 2.1.3: *Location of the Catalão I deposit. Modified after Google Maps (2016)*

This deposit is in the first place a niobium (columbium)/phosphor mine and produces minor quantities of REE (cerium (Ce)) and titanium (Ti). The owner of the mine is Mineração Catalão De Goías S. A. (Mcg) and they are producing 1513 metric tons ore per day (USGS, 2016). Total resources are 119 Mt of an average of 5.5% grade REE_2O_3 (Ribeiro, 2008) while current highest grade reserve is estimated on 2 Mt laterite of 12% REO (Castor, 1994). Within the deposit, there are also some lower grade REEs present. These have been estimated at 4.6Mt of 4% REO (Azevedo Branco, 1984) and 21 Mt of 1.02% REO (Singer, 1998).

Within this deposit, just like the Araxá deposit, monazite is the main REE carrier. Monazite occurs here as pockets of aggregated minerals dispersed in the weathering profile and also locally concentrated in the silcrete layers (Neumann, 1999; Ribeiro, 2008). Silcrete is formed in aluminum-depleted rocks with silica released from silicate minerals during the weathering process (otherwise it usually forms kaolinite) (Morteani and Preinfalk, 1996; Oliveira and Imbernon, 1998). Other REE containing minerals are: Ce-Ba-pyrochlore (Ce, Ba)-$(Na,Ca)_2Nb_2O_6(OH,F)$, gorceixite, apatite, florencite, ancylite, goyazite, anatase (TiO_2) and rhabdophane ($(Ce, La)PO_4 \bullet (H_2O)$) (Orris and Grauch, 2002).

Catalão II

15 kilometers north-west from the Catalão I deposit, lays the Catalão II deposit. The Catalão II intrusion consists of a primary ultramafic phase, composed essentially of pyroxenites, foscorites and syenites. The carbonatitic intrusions at Catalão II occupy a relatively smaller volume, with the preservation of much of the ultramafic rocks (Porter Geoconsultancy, 2016). The age of the deposit is 87.1 Ma, dated from the Campanian, Upper Cretaceous. The Catalão II deposit is also a Niobium- and REE-bearing carbonatite, which is hosted in sovite, phoscorite and glimmerite[1] (Orris & Grauch, 2002). This mine is also owned by Mineração Catalão De Goías S. A. (Mcg) and has a primary production of Niobium and the REEs are produced as REE-phosphates. The estimation of total REE_2O_3 is 25 Mt with a grade of 0.98% (Machado Junior, 1991). Furthermore, the deposit contains 400 Mt P2O5 (9,5%) and 13.5 Mt Nb2O5 (1,35%) (Machado Junior, 1991). Other minerals which occur within the deposit are; magnetite, pyrochlore, vermiculite, barite and barium-pyrochlore (Orris & Grauch, 2002).

Figure 2.1.4 shows the location of the Catalão II deposit.

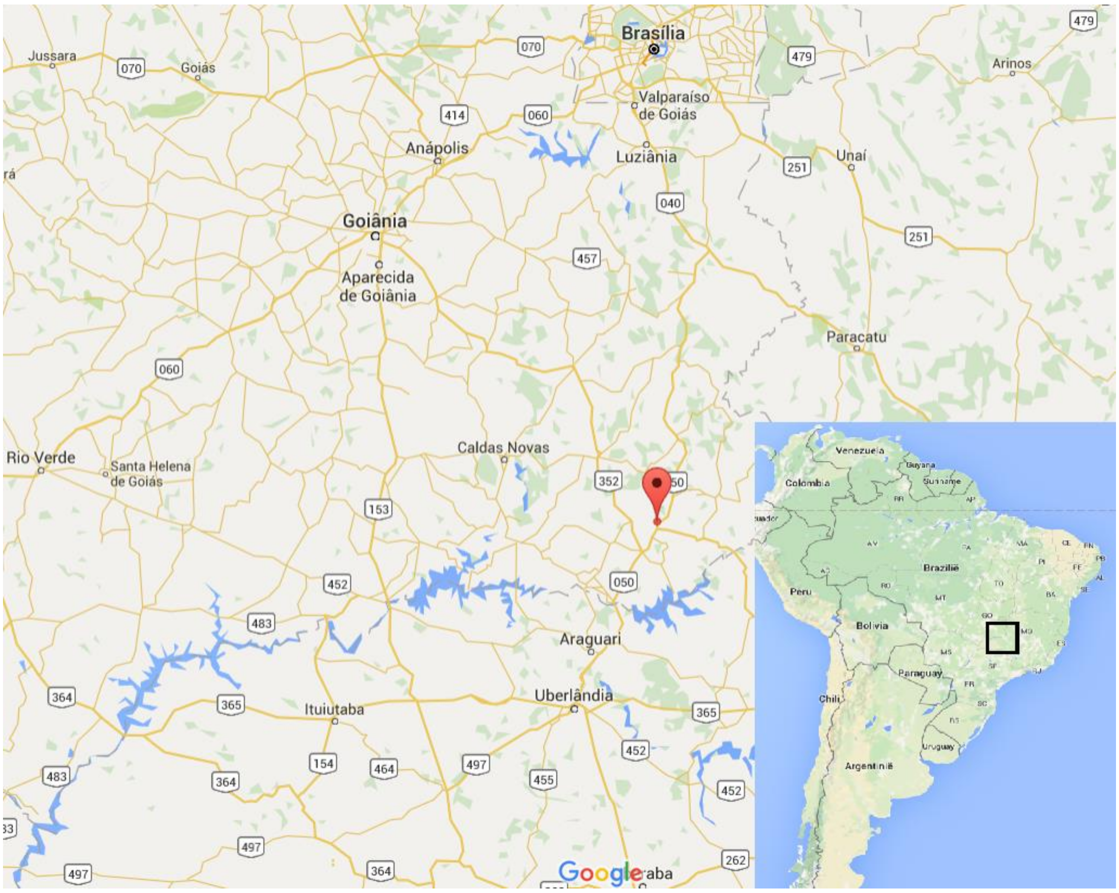

Fig. 2.1.4: *Location of the Catalão II deposit. Modified after Google Maps (2016)*

[1] glimmerite: 'An ultrabasic igneous rock, consisting almost wholly of essential dark mica, either phlogopite or biotite. These rocks are rather rare, being found among ultramafic xenoliths in kimberlite pipes and within old basement gneisses. These occurrences testify to the deep-seated origin of glimmerites, which might be considered as metamorphic rather than igneous' (Allaby, 1999).

Morro dos Seis Lagos

The Morro dos Seis Lagos deposit (Previously listened to the name of 'São Gabriel Da Cachoeira') (USGS, 1992) located in the northern part of the Amazonas province is an iron carbonatite deposit with siderite as the main mineral and is covered by a thick ferruginous lateritic crust. The deposit hosts one of the largest Niobium deposits in the world, with a measured Nb reserve of 2.9 billion tons (Gt) of 2.81% Nb2O5. It also hosts iron and manganese deposits with inferred reserves of 8 Gt of 50.0% Fe2O3 and 0.32 Mt of more than 40.0% MnO2, respectively (Justo, 1983).

Figure 2.1.5 shows the location of the Morro dos Seis Lagos deposit. It also shows that the deposit lies within the 'Parque Nacional do Pico da Neblina' which is considered to be indigenous land.

Fig. 2.1.5: *Location of the Morro dos Seis Lagos deposit. Modified after Google Maps (2016)*

Within the deposit is an occurrence of REE-bearing minerals. The main REE carrying ore minerals are monazite and its alteration products, such as florencite and rhabdophane. Also some REEs can be found in the romanechite group and pyrochlore minerals (Sousa, 1996). The estimated resource for these REEs is 43.5 Mt of 1.5% REE oxides (Sousa, 1996). This makes the Morro dos Seis Lagos one of the main REE deposits of Brazil. However, this deposit has legal issues because it lies in indigenous land (Takehara, 2014).

Poços de Caldas

Another main deposit of Brazil's REE is the Poços de Caldas deposit. This is an alkaline-igneous deposit lying on the border of the Minas Gerais and the São Paulo. The deposit lays in a circular structure which resembles a collapsed caldera, approximately 30 kilometers in diameter. The alkaline complex consists mainly of tinguaite, phonolite and nepheline-syenites and sodalite-syenites. The Poços de Caldas deposit was once one of the world's largest baddeleyite deposits but is now nearly depleted (Castor, 1994). Also the deposit was exploited for mining zircon, bauxite and uranium. That mine is now abandoned (mindat.org, 2016).

Figure 2.1.6 shows the location of the Poços de Caldas deposit.

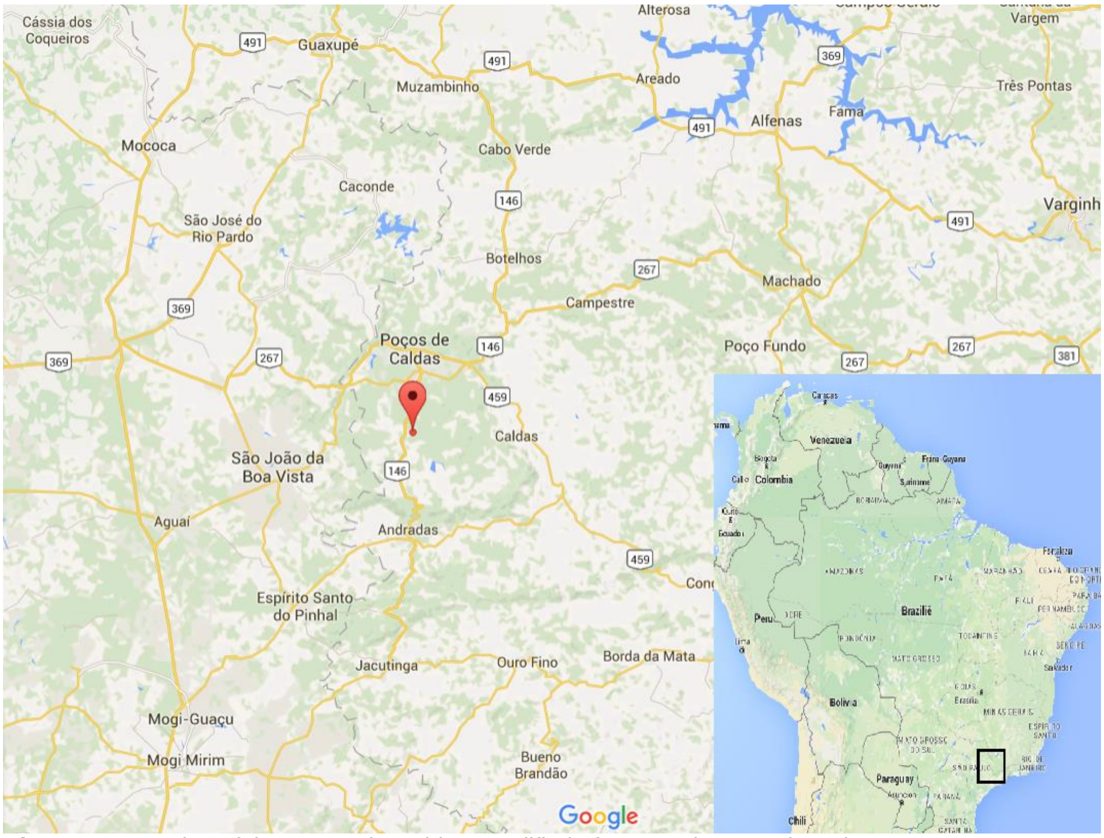

Fig. 2.1.6: *Location of the Poços de Caldas. Modified after Google Maps (2016)*

The main REE carrying mineral is bastnaesite and the ore occurs as 1 Mt at 4% REO in a central core (Roskill, 1988), with a halo of 0.5 Mt at 1.75% REO (Jackson and Christiansen, 1993). These are the reserves. The total resource of the deposit is 7.0 Mt REE_2O_3 at an average grade of 2.89% (EDEM, 2013).

These are the 'main' Brazilian carbonatite deposits and occurrences. Table 2.1 shows the estimation of the total REE mineralization within these deposits and occurrences. Note: there are more carbonatite deposits containing REE-bearing minerals. But these are considered to be of less potential and have not been studied exhaustively. Nevertheless the known data is shown in appendix A.

Table 2.1: *Estimation of REE mineralization within the 'main' carbonatite deposits and occurrences in Brazil.*

Name	Total REE_2O_3 (ore grade)	Main REE carrying minerals	Other Mineralization (ore grade)
Araxá	22 Mt (3.02%)	monazite, goyazite	210 Mt P_2O_3 (>10%); 462 Mt Nb_2O_5 (2.5%, residual); 51 Mt $BaSO_4$ (7.26%)
Barra do Itapirapuã	44.8 Mt (0.7%)	bastnaesite, ancylite, synchysite, parisite	P, Pb and fluorite.
Catalão I	119 Mt (5.5%)	monazite, goyazite, Ce-Ba-pyrochole, gorceixite, apatite, florencite, ancylite, anatase, rhabdophane	250 Mt P_2O_3 (10.48%); 19 Mt Nb_2O_5 (1.8%); 161 Mt TiO_2 (>10%); 35.9 Mt vermiculite (17%)
Catalão II	25 Mt (0.98%)	REE-phosphates	400 Mt P_2O_3 (9.5%); 13.5 Mt Nb_2O_5 (1.35%
Morro dos Seis Lagos	43.5 Mt (1.5%)	monazite, florencite, rhabdophane	2.9 Gt Nb_2O_5 (2.81%); 8 Gt Fe_2O_3 (50%), 0.32 Mt MnO (>40%)
Poços de Caldas	7.0 Mt (2.89%)	bastnaesite	26.8 Mt of U_3O_8, 25 Mt of MoO_2, and 172.4 Mt of ZrO_3
Total	261.3 Mt (ranging from 0.7% to 5.5%)	-	-

2.1.2. Granitic Deposits

The second primary sources of REE-bearing mineral deposits are the granitic deposits. These granitic deposits are more related to the HREEs. Source rocks and magma formation processes have important roles in governing initial REE concentrations of granitic deposits (Hannah & Stein, 1990). As an example we take the extent of partial melting, which is influenced by timing, volume and mechanism of fluid release (Hannah and Stein, 1990). REE deposits are usually associated with multiphase an-orogenic granite complexes in which the latter stages of magma crystallization are highly enriched in incompatible elements, including REEs. The granitic complexes usually have vertical- and occasionally lateral zoning, with nicely developed mineralogical, textural and modal variations in composition. Within Brazil, the REE-enriched granites are the most fractionated members of the granite group (Pollard, 1995). That these fractionated granites are highly REE-enriched is no coincidence. Similarly to the carbonatite deposits from section 2.1.1, this has everything to do with weathering. However, the HREE are generally concentrated in the lower part of this profile in the granite saprolitic zone, forming the REE ionic clay deposit (Long et al., 2010; Santana, 2013). These ionic clay deposits overlying granite rocks generally have low mining costs (Wu et al., 1996; Santana, 2013). Other than ionic clay deposits, granite REE minerals (mainly xenotime) can also form REE alluvial deposits (Pollard, 1995).

Out of these granitic deposits are two deposits potentially interesting, these are the deposits within the Pitinga Sn-mine and within the Serra Dourada granite. These deposits are described below.

Pitinga

Within the region of the Amazonas, 300 kilometers from Manaus, the company Mineração Taboca S.A. discovered in the 80's the Pitinga tin-mine. Within this tin-mine cassiterite and columbite ore are being mined and processed. (Mineração Taboca S.A., 2016). This deposit is formed by large volcanic and plutonic bodies of rock (Costi et al., 2005). The lithology of the Pitinga deposit is mainly composed of acid volcanic rocks from the Iricoumé group which are intruded by multiphase igneous rocks of the Madeira suite (Lenharo et al., 2003; Costi et al., 2005). This Madeira suite exists of the Madeira granite, the Água Boa granite and the Europe granite have an age of approximately 1.82 Ga and are dated from the Paleoproterozoic (Costi, 2000).

Figure 2.1.7 shows the location of the Pitinga mine.

Fig. 2.1.7: Location of the Pitinga deposit. Modified after Google Maps (2016)

The Madeira and Água Boa granites are mineralized with REEs in an elongated form parallel to major regional faults which are believed to have controlled these intrusions (Lenharo et al., 2003). An exploratory survey performed by Taboca Mining has indicated that Pitinga has economic potential for REE extraction. The REE minerals here are xenotime, gargarinite ($NaCaYF_6$) and fluocerite ($(Ce,La)F_3$) (Garcia, 2012). The main REE mineral in the (albite) granite of the Madeira complex is xenotime. Chemical and mineralogical analyses of this xenotime have indicated a high concentration of HREEs (yttrium (Y), dysprosium (Dy), terbium (Tb)). The content of the total REE is approximately 98% HREE and only 2% LREE. This offers a very positive economic potential, as these elements are considered to be critical REEs (Garcia, 2012). The big advantage is that the Pitinga project can produce REE as a byproduct of Sn, Ta and Nb, which minimizes the mining cost. (Takehara et al., 2014) This potential byproduct has an estimated resource of 2 Mt of 1% grade Y_2O_3 (Garcia, 2012). A large disadvantage which occurs in the Pitinga mine is that the deposit contains radiogenic elementals (principally Thorium). The removal and disposal of these radiogenic elements cost a lot of money which has a negative influence on the potentiality of the deposit (Takehara et al., 2014).

Serra Dourada

Within the province of Goiás (often referred to as the Tin (Sn) province) are a lot of REE resources located. The largest one is within the Serra Dourada granite. The Serra Dourada granite is one of the most REE-enriched granites of this province and locally reaches REE contents of almost 2000 ppm (Polo and Diener, 2013). This granite has been exploited for Sn until the 1990s and afterwards for emerald and amazonite (Marini et al., 1992). The northern part of the Serra Dourada granite is being exploited by Mata Azul mining and the southern part of the granite is in hands of the Serra Verde mining company (Brasil Mineral Online, 2014).
Figure 2.1.8 shows the location of the Serra Dourada mine from Serra Verde Mining (SVM).

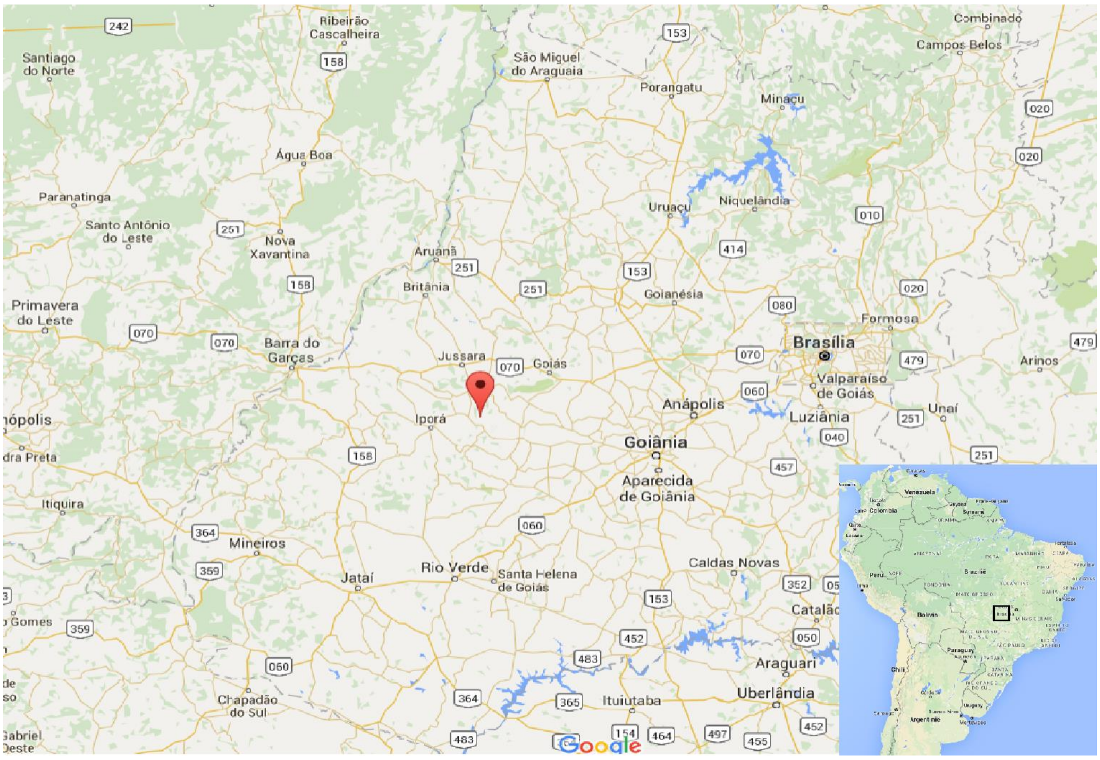

Fig. 2.1.8: *Location of the Serra Dourada deposit. Modified after Google Maps (2016)*

The REE-bearing minerals in this granite are monazite, xenotime, zircon, allanite, apatite, bastnaesite and fluocerite (Teixeira and Botelho, 2006). The main primary REE minerals are monazite and xenotime (Santana, 2013). These can be found in fresh biotite granite, in the saprolitized rock and as heavy minerals in fluvial placer deposits.

The southern part of the Serra Dourada granite has been explored by Serra Verde Mining and the mining project is focused on the saprolitic zone of this granite. The company will exploit primary REE-bearing minerals such as xenotime, monazite, fergusonite, and minor allanite and pyrochlore and secondary minerals including bastnaesite and REE-adsorption clays (Takehara et al., 2014). The reserve is composed of 70% LREEs and 30% HREEs. Within these occurrences there is a high content of critical REEs (Neodymium (Nd), Europium (Eu), Erbium (Er), Dysprosium (Dy) and Yttrium (Y)) which makes this deposit even more economically interesting. In addition to this, Niobium (Nb) will be mined as a byproduct (Takehara et al., 2014). The estimated total reserves are approximately 412 Mt of 0.16% REEs (Mineração Serra Verde, 2014).

These are the two 'main' Brazilian granitic deposits. Table 2.2 shows the estimation of the total REE mineralization within these deposits. Note: there are more granitic deposits containing REE-bearing minerals. But these are considered less potential and have not been studied exhaustively. Nevertheless, once again, as with the carbonatite deposits, the known data is shown in appendix A.

Table 2.2: *Estimation of REE mineralization within the two 'main' granitic deposits in Brazil.*

Name	Total REE_2O_3 (ore grade)	Main REE carrying minerals	Other Mineralization (ore grade)
Pitinga	2 Mt (1.0% of Y_2O_3)	xenotime, gargarinite, fluocerite	189 Mt of Sn; 35 Mt of Ta_2O_5; 9 Mt Na_3AlF_6 (31.9%)
Serra Dourada	412 Mt (0.16%)	monazite, xenotime, zircon, allanite, apatite, bastnaesite, fluocerite	niobium
Total	414 Mt (fairly low in grade)		-

2.1.3. Placer Deposits

Placer deposits are one of the easiest for exploiting heavy minerals. REEs occur within these heavy mineral or marine placer deposits and are distributed along the Brazilian marine coast, ranging from Pará to Rio Grande do Sul (Cavalcanti, 2011). Minerals that have been mined throughout the world from beach sands include ilmenite, rutile, zircon and monazite (Dardenne and Schobbenhaus, 2001), with monazite being a REE-bearing mineral. The origin of these heavy minerals is again mainly related to weathering: the weathering of continental igneous rocks which crystallized during orogenic events. Erosion of these rocks resulted in heavy mineral deposits which mainly concentrated along the Brazilian coastline. These deposits are aging from the Tertiary period; such are the Barreira group, which, we will see, is the host group of a lot of shoreline deposits described below (Takehara et al, 2014).

Placer deposits used to be the first deposits to be mined for REEs. In wet environments, heavy mineral sand placers are mined by dredging techniques, applying (in deeper water) bucket line and suction dredges or (in shallow water) bucket wheel units. In dry conditions, open pit methods are used. Drilling and blasting are generally not required as these placer deposits are often poorly-, or not consolidated (Voncken, 2016). These mineral sands were afterwards processed as-mined and not subjected to any comminution (Gupta & Krishnamurthy, 2005).

The placer deposits within Brazil were important until mid-1950s, when monazite was produced in Brazil. The production of REEs of this placer deposit type was stopped in 2002 (Serra, 2013) when they were replaced by primary ores such as monazite and bastnaesite from the Mountain Pass carbonatite (USA). Currently, marine placers have been mined mainly for titanium minerals in the provinces of Rio de Janeiro and Paraíba (Cavalcanti, 2011). Nevertheless it is useful to have a look at some main-placer deposits and what is left of them, to indicate the REE resources and reserves of Brazil.

Anchieta

The Anchieta deposit is a shoreline placer deposit located in the province of Espirito Santo, along the coast of the Southern Atlantic Ocean. It was discovered in 1880 and is dated from the Late Tertiary (diggings.com, 2016).

Figure 2.1.9 shows the location of the Anchieta shoreline placer.

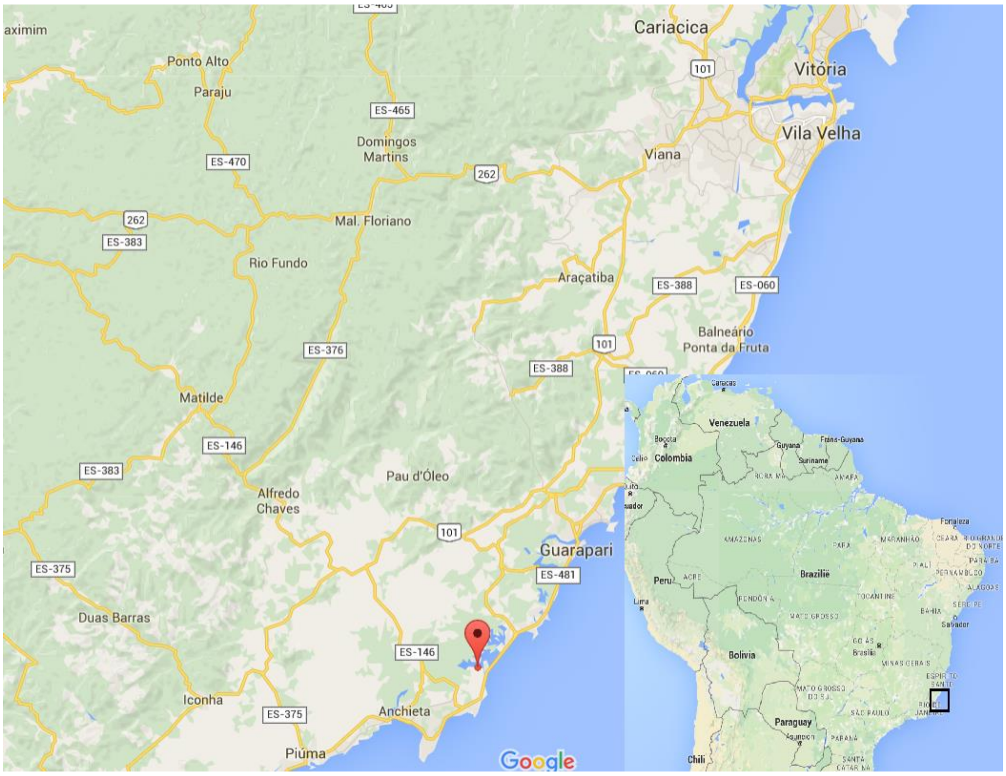

Fig. 2.1.9: *Location of the Anchieta shoreline placer deposit. Modified after Google Maps (2016)*

REE have been found here in the form of monazite, hosted in the Barreira group and some younger sediments (Anstett, 1986) It is a past producer deposit site where REE, zircon, rutile and ilmenite were mined (diggings.com, 2016). The company producing ore within the mine was Nuclebrás de Monazita e Associados Ltda.

The measured reserves were 698 t monazite grading 60.02% REO in 1986 (Roskill, 1988) and 0.057 Mt monazite of 0.71% grade in 1987 (Jackson & Christiansen, 1993). The deposit exists of small modern beach placers, which are elevated bars. The monazite contained about 5.2% ThO2. The deposit has now been mostly depleted (Jackson & Christiansen, 1993).

Aracruz
Another placer deposit from the Barreira group, located in the province of Espirito Santo, is the Aracruz deposit. Also discovered in 1880 (Azevedo Branco, 1984).
Figure 2.1.10 shows the location of the Aracruz shoreline placer deposit.

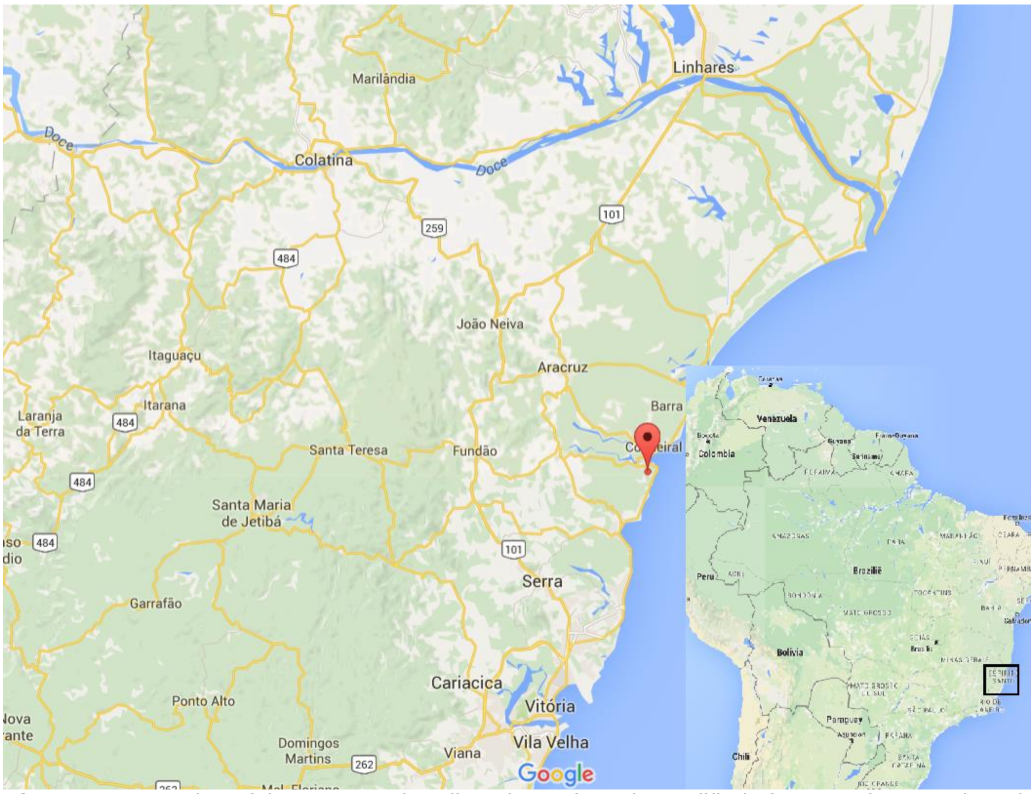

Fig. 2.1.10: *Location of the Aracruz shoreline placer deposit. Modified after Google Maps (2016)*

The measured reserves are 2964 tons of monazite grading 59.98% REO (Roskill, 1988) and 0.282 Mt monazite of 1.05% grade (Jackson & Christiansen, 1993). The monazite within this deposit used to be mined as a byproduct, along with ilmenite, rutile and zircon by the company Nuclebrás de Monazita e Associados Ltda (Orris & Grauch, 2002). Although there is still some monazite left in the deposit, there is little likelihood that this deposit will be developed unless additional resources are found in the area (Diggings.com, 2016).

Guarapari
Yet another deposit owned by Nuclebrás de Monazita e Associados Ltda. Located in the province of Espirito Santo is the Guarapari shoreline deposit. This deposit is an unconsolidated deposit, which contains sediments of the Barreira group and some younger units (Orris & Grauch, 2002). The age of this deposit however is Quaternary instead of Tertiary.
Figure 2.1.11 shows the location of the Guarapari deposit.

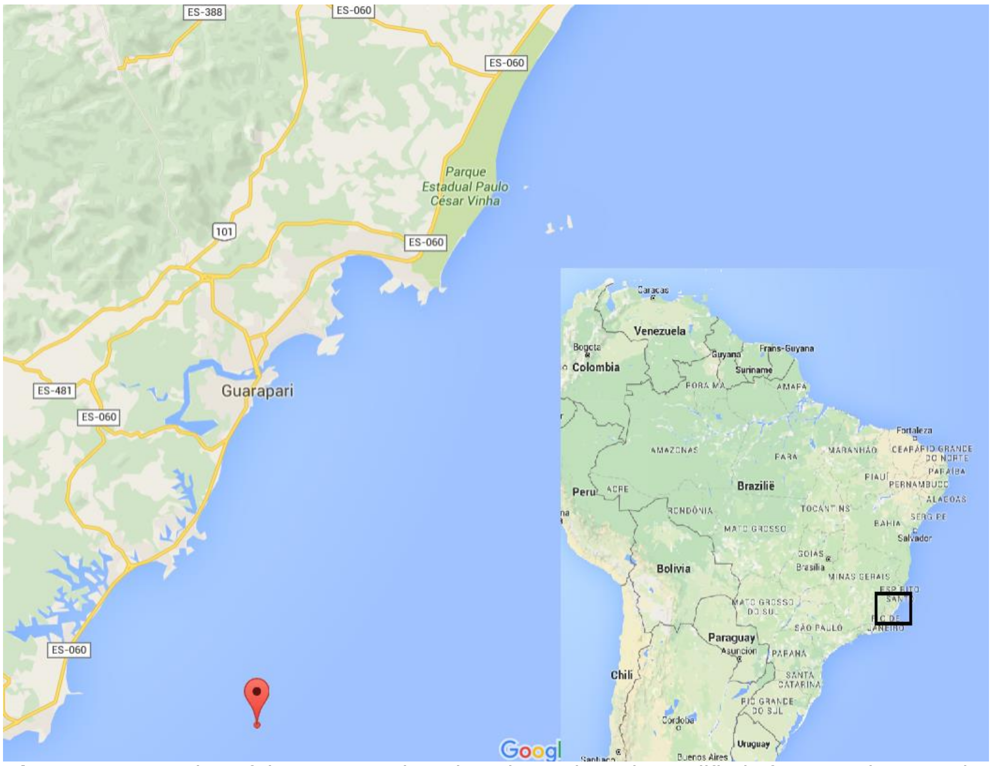

Fig. 2.1.11: *Location of the Guarapari marine placer deposit. Modified after Google Maps (2016)*

The deposit contains mainly heavy minerals like ilmenite, zircon, rutile and magnetite, but also the REE-bearing mineral monazite. The measured reserves of the Guarapari deposit were 818 tons monazite with an REO grade of 60.04% in 1986. And in 1987 this got adjusted to 950 t monazite (Roskill, 1988; Jackson & Christiansen, 1993). The main REE within this monazite is cerium (Ce).

Prado

Leaving the province of Espirito Santo behind, moving northward, located in the state of Bahia, another placer deposit is located near Prado. This is a quite recent deposit consisting of beach sands and is yet again property of Nuclebrás de Monazita e Associados Ltda.
Figure 2.1.12 shows the location of the Prado deposit.

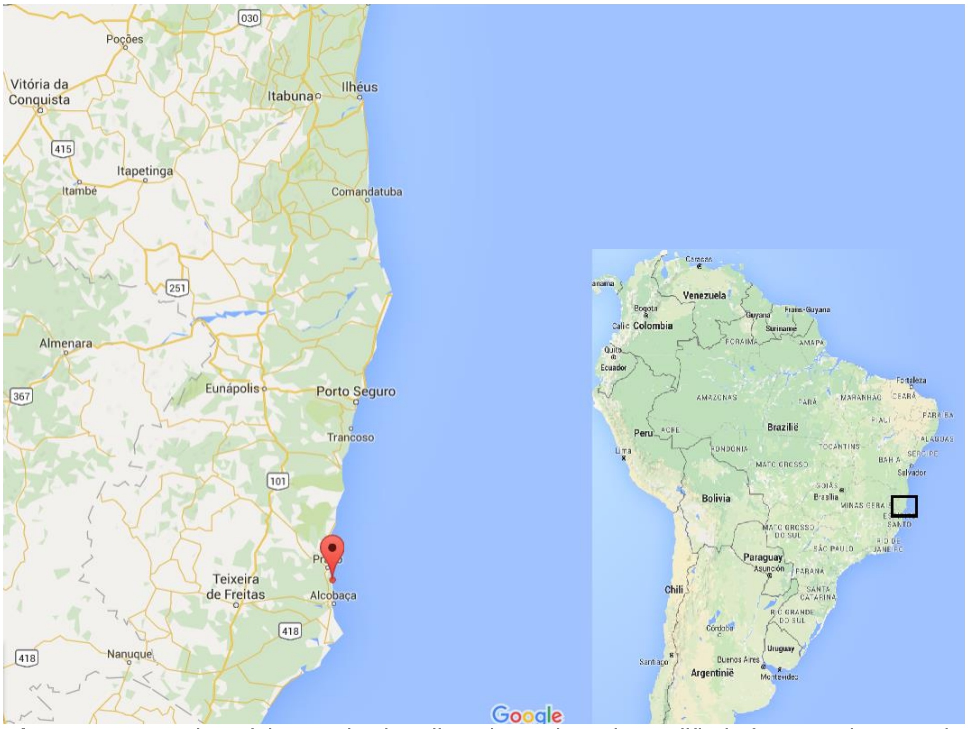

Fig. 2.1.12: *Location of the Prado shoreline placer deposit. Modified after Google Maps (2016)*

According to Jackson & Christiansen (1993), the measured reserves for this deposit are 4564 t of monazite grading 19.98% REO. Besides monazite, this beach sand also contains two other REE-bearing minerals, namely xenotime and allanite. These REE-bearing minerals used to be produced as a byproduct in a thorite mine, along with ilmenite, zircon, spinel and garnet (Orris & Grauch, 2002). The current status gangue minerals are quartz, staurolite and kyanite.

São João da Barra
The last placer deposit within Brazil which will be described is the São João da Barra deposit, located, a little bit more land inward, in the state of Rio de Janeiro. The age of the deposit is Tertiary/Quaternary, so geologically speaking, quite a recent deposit. The deposit is part of the Barreira group (which we have seen before), and some younger sediments and beach sands (Hedrick & Templeton, 1991).
Figure 2.1.13 shows the location of the São João da Barra deposit.

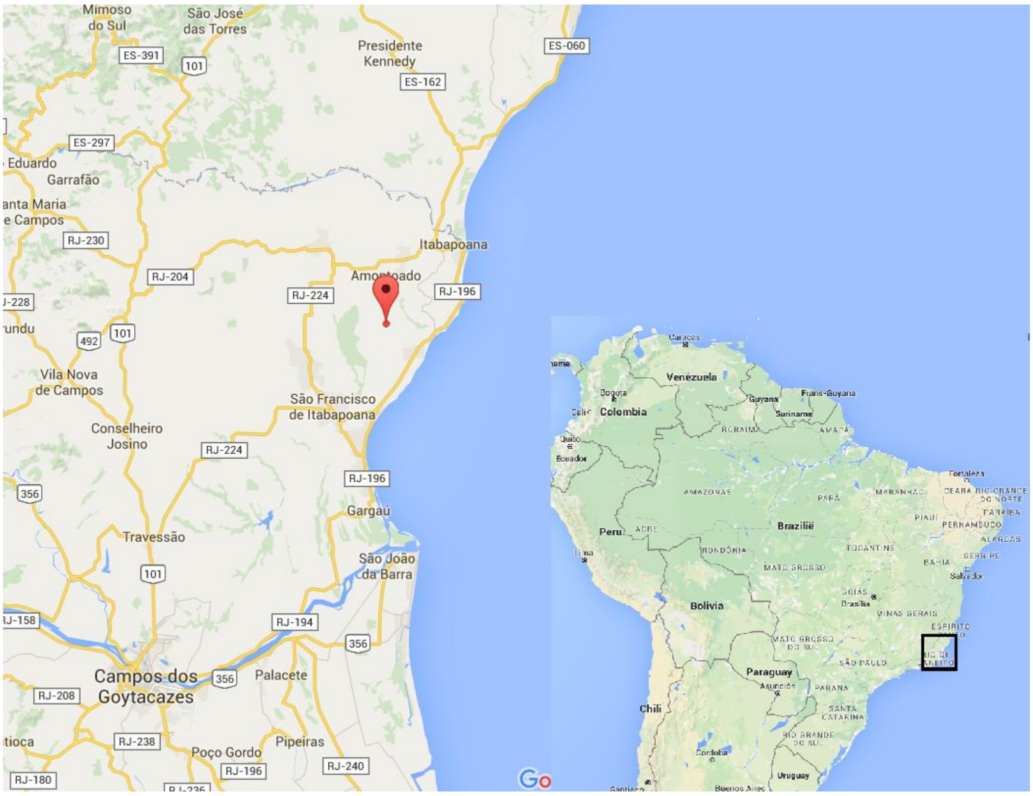

Fig. 2.1.13: *Location of the São João da Barra deposit. Modified after Google Maps (2016)*

This deposit is a producer of monazite as a byproduct and is owned by the company Nuclebras de Monazita e Associados Ltda. Other minerals that are being produced are ilmenite and zircon (Overstreet, 1967). The measured reserves of this deposit are 8177 tons monazite with a grade of 59.99% REO (Roskill, 1988).

Placer deposits are normally not that large in size, at least not as large as the granitic- or carbonatite deposits. They were also the first type of deposit that has been exploited in Brazil for REEs. The reason why these deposits were the first type to be exploited is that they are easily mined, so the mining costs are fairly low. That is why a lot of the deposits are (half-) depleted, and estimations made below in table 2.3 may not be that accurate, as these estimations were done during, or before exploitation. The only disadvantage of these deposits is the size, as it is most of the time not economically viable to set up a whole mining operation, just for the REE-bearing mineral ore. That is why the REE-bearing minerals have mostly been won as byproducts.

Table 2.3: *Estimation of REE mineralization within the 'main' placer deposits in Brazil.*

Name	Total REE_2O_3 (ore grade)	Main REE carrying minerals	Other Mineralization
Anchieta	698 t (60.02%) 57.000 t (0.71%)	monazite	Ilmenite, rutile, zircon, thorianite
Aracruz	2964 t (59.98%) 282.000 t (1.05%)	monazite	Ilmenite, rutile, zircon
Guarapari	950 t (mainly Ce) (60.04%)	monazite	Ilmenite, rutile, zircon, magnetite
Prado	4564 t (19.98%)	monazite, xenotime, allanite	Ilmenite, zircon, spinel, garnet, thorite
São João da Barra	8177 t (59.99%)	monazite	Ilmenite, zircon
Total	356.353 t (of which 95% ≈ 1% REO)	-	-

2.1.4. Other Deposits

Within Brazil, research for new REE deposit continues as demand for the application of these elements increases. This resulted in the discovery and exploitation of some new deposits. Two of which will be discussed below.

Serra do Ramalho

Recently, only in April 2012, the World Mineral Resources (WMR) has announced that it had found a large reserve of neodymium (Nd) hosted in rocks composed of calcium fluoride in Serra do Ramalho within the Western Bahia State of Brazil (mining.com, 2012).
Figure 2.1.14 shows the location of the Serra do Ramalho deposit.

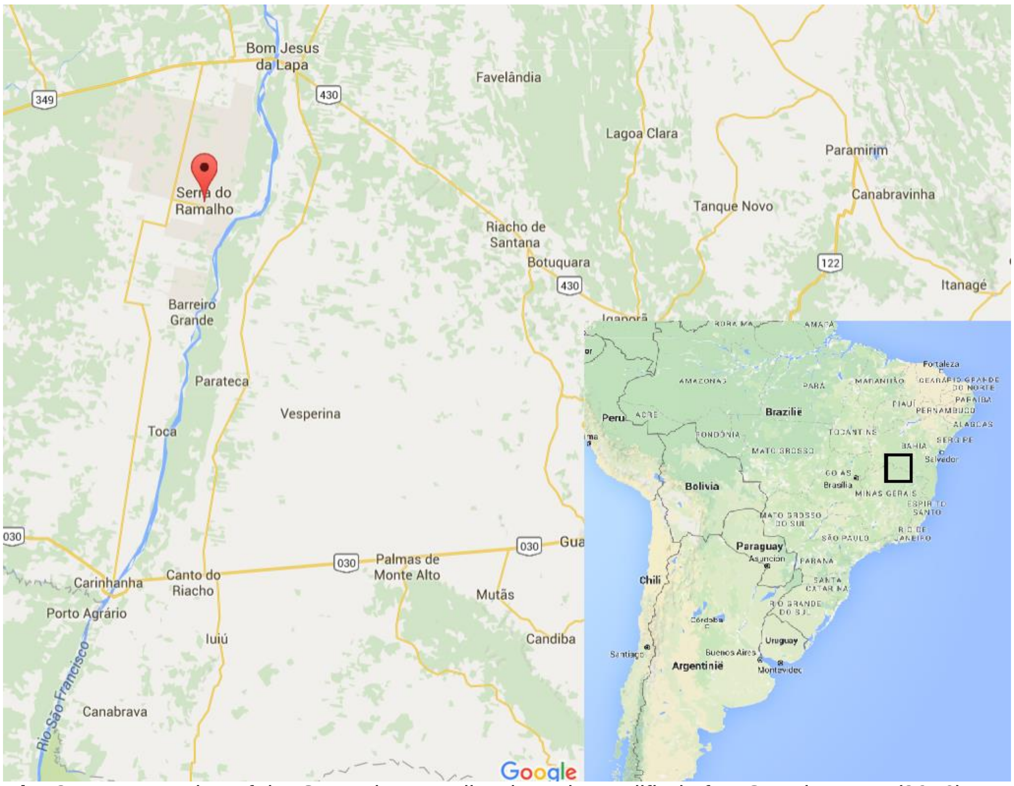

Fig. 2.1.14: *Location of the Serra do Ramalho deposit. Modified after Google Maps (2016)*

This is the first Neodymium deposit discovered within Brazil and its resources are estimated at 28 Mt. Something very special about the ore is that the Nd concentration levels are similar to the leading Chinese neodymium ore. In the Western Bahia State, the ore has been found grading levels of 12.75% while the Chinese neodymium grades are in the range of 12-14%. This is a very positive sign for Brazil to compete with China on the global REE market. Further study has to determine the exact size of the reserve, but at current market prices the 28 Mt of Nd deposit could bring in $8.4 billion (BNamericas, 2012).

Salobo

In the south-eastern part of the Pará state next to the town of Marabá lays Vale’s largest copper operation. The Salobo iron-oxide copper mine went into operation in November 2012 (Vale, 2015).

Figure 2.1.15 shows the location of the Salobo deposit.

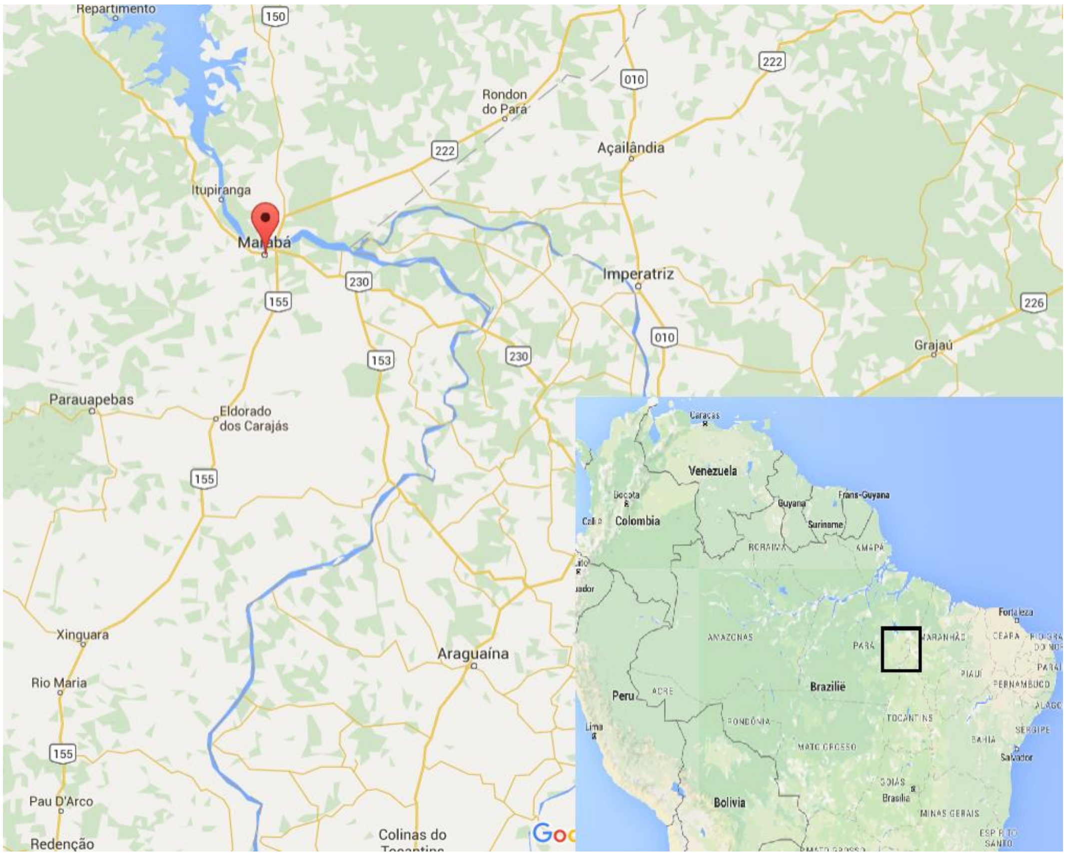

Fig. 2.1.15: *Location of the Salobo deposit. Modified after Google Maps (2016)*

Vale has discovered a rich deposit of rare earth minerals within the mine (The Street, 2011). On its own, it is not feasible to mine the quantity of Rare Earth Elements within the Salobo copper mine. However, the main production of the mine is based on copper ore (capacity of 100 kt/year with 65 kt in 2013 and 40.8 kt in the first half of 2014) and the REE bearing minerals are being mined as a byproduct (Vale, 2015). Exact quantities of REE reserves and resources within the Salobo copper mine are unkown[2].

[2]. Could not be found in the available English literature.

2.1.5. REE potentiality within other parts of South America

There might be more potentially feasible REE resources located in the rest of South-America, but the main REE country irrefutably is Brazil. Throughout my description of the REE-bearing deposits and occurrences I noticed that there might be some more potential for REE resources.

The Madeira suite, which hosts the Pitinga deposit, is part of a larger whole. This 'whole' is called the Guyana (Guiana) Shield and is formed of bodies of volcanic and plutonic rocks (Costi et al., 2005). As described above, these bodies host granites which are mineralized with REEs. However, the Guyana Shield covers only a small part of Brazil. The Guyana Shield, also called Guyana Highlands, covers French-Guyana, Suriname, Guyana, a part of Venezuela and even a small part of Colombia, which you can see in Figure 2.1.16.

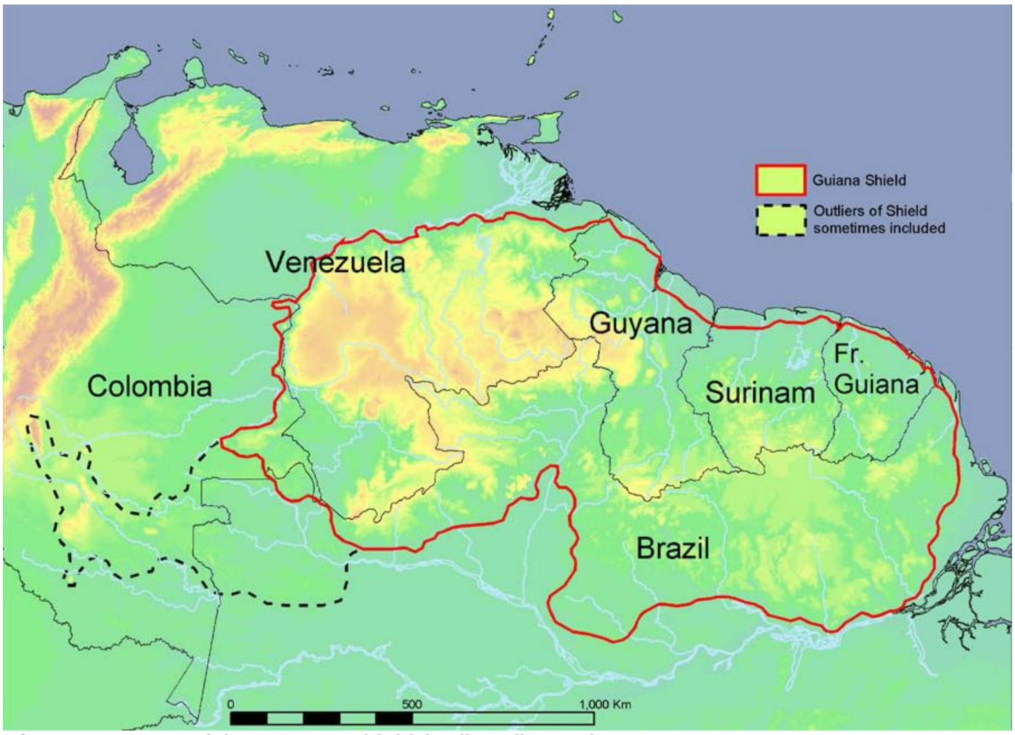

Fig. 2.1.16: *Map of the Guyana Shield (Hollowell, 2011).*

The Guyana shield is largely mineralized. The Guyana shield mainly attracted international interest due to the gold, bauxite and diamond deposits which can be found. The shield also is known for containing semi-precious stones, laterite, manganese, kaolin, sand resources, radioactive minerals, copper, molybdenum, tungsten, iron and nickel. Guyana produced nearly 1.6 million metric tons of bauxite, 7442 kg of gold and 356,950 metric carats of diamonds (Guyana office for investment, 2016). Also, as mentioned at the Pitinga deposit, this region carries a lot of Sn-mineralization (Tin-Province).

Linking the properties of large quantities of different mineralization and the characteristics of the volcanic and plutonic rock bodies indicates that there might be some more REE mineralization in the Guyana Shield, other than the southern part in Goías, Brazil. There are still a lot of undiscovered deposits abundant in the Guyana Shield. It is estimated that there is at least a 50% probability of finding five or more additional (carbonatite) bodies with a median tonnage of niobium and REE-bearing zones of about 60 million tons in the Venezuelan part of the Guyana Shield alone (United States Geological Survey et al., 2012). Also, close to Port Kiatuma in Guyana, a new deposit of Precambrian tin-province bearing columbite and tantalite was discovered. According to estimates by the Guyana Geology and Mines Commission the estimated resource are in excess of $10 million dollars (mining.com, 2012). These columbite-tantalite bodies are closely associated with quartz-casserite veins. Minerals from weathered cassiterite-pegmatites may concentrate in streams as gravels or form placer deposits. These placer deposits, as one saw at chapter 2.1.3, may contain ilmenite, zircon, as well as columbite-tantalite and monazite. Monazite is the main REE-bearing mineral in these placer deposits and these deposits are significant sources and may contain notable amounts of REEs (Guyana office for investment, 2016). Therefore, there might still be a lot more potential considering the aspect of REE resources in South America.

2.2 India

The proven REO reserves for India are around 3.1 Mt, which is around 2.2% of the world total (USGS, 2016). The REE resources for India are considerably lower than for Brazil, or China for that matter (Chen, 2011). However, the production is with 2900 tons/year, notable larger than that of Brazil. This has to do with the type of deposit that is being mined. As one can see in Appendix B, the main occurrences for REE-bearing minerals are mostly situated within (shoreline) placer deposits. As told before, these placer deposits are looser sediments and mostly situated relatively shallow in the subsurface which make them easier and cheaper to mine. The Saranu deposit and the Kamthai deposit located in Rajasthan are two of the few known significant carbonatite deposits within India that carry notable concentrations of REE (≥5% REO). This is contrary to Brazil, in which the placer deposits are a secondary source of REE, while the carbonatites are the main REE-bearing deposits.

There are four operations that are engaged in commercial scale processing of monazite sands in India. These operations are state owned by Indian Rare Earths Limited (IREL). Two of these operations are located at Aluva and Chavara in the state of Kerala. The other two are located at Manavalakurichi in Tamil Nadu and at Chatrapur in Orissa (Mining-Technology, 2014). The last one is IREL's biggest producing mine.

2.2.1 Carbonatite Deposits

Saranu

As described before, the Saranu deposit located in Rajasthan is one of the only known significant carbonatite deposit within India that carries notable concentrations of REE. The deposit contains ≥5.5 % REO and they are hosted in carbonatite dikes of about 10 centimeters wide (Wall & Mariano, 1996). The REE-bearing minerals are carbocers, these are minerals consisting of a carbonaceous, ocherous or pitchy substance containing rare-earth elements (Merriam-Webster, 2016). Another mineral present within these carbonatite dikes is strontiane. The rock forming mineral is obviously calcite. Exact tonnages of REE-bearing material in the Saranu deposit are unknown[3].

Figure 2.2.1 shows the location of the Saranu carbonatite deposit.

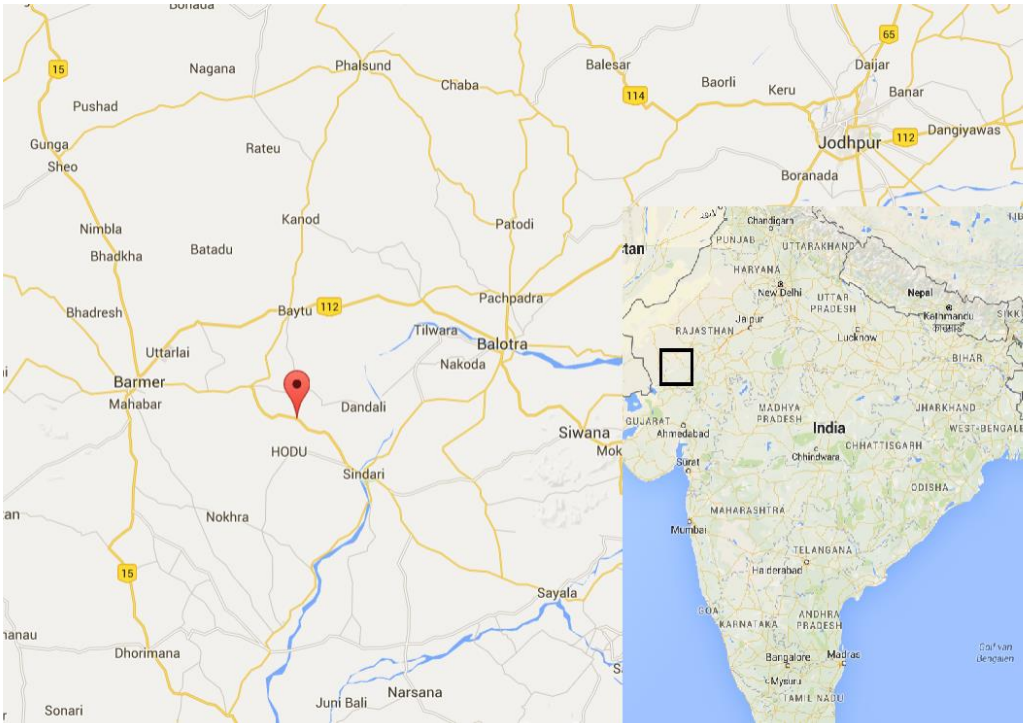

Fig. 2.2.1: *Location of the Saranu deposit. Modified after Google Maps (2016)*

[3]. Could not be found in the available English literature.

Kamthai

A much more recently discovered deposit has been found by geological mapping and grid channel geochemical sampling (Bhushan & Kumar, 2013). It is a carbonatite plug at Kamthai, Barmer district, in Rajasthan (very close to the Saranu deposit).
Figure 2.2.2 shows the location of the Kamthai carbonatite deposit.

Fig. 2.2.2: Location of the Kamthai deposit. Modified after Google Maps (2016)

The main REE minerals hosted by this plug are bastnaesite (La), bastnaesite (Ce), synchysite (Ce), carbocernaite (Ce), verianite (Ce), ancylite and parisite (Bhushan & Kumar, 2013). The highest value of LREE is 17.31% and the mean grade is 3.33%. The carbonatite plug covers 19.475m^2 and the total resource estimation (plug and other sills, dykes and veins) is 4.91 Mt (Bhushan & Kumar, 2013). For the plug only, the total content of individual LREO is shown in table 2.4.

Table 2.4: *Estimation of individual REEs and other elements within the carbonatite plug deposit of Kamthai, India.*

Name Element	Total Tonnage
La (Lanthanum)	52.196 t
Ce (Cerium)	66.026 t
Nd (Neodymium)	13.663 t
Pr (Praseodymium)	5.415 t
Sm (Samarium)	920 t
Eu (Europium)	207 t
Other Elements	-
Ga (Gallium)	551 t
Ge (Germanium)	44 t
SrO (Strotium Oxide)	112.830 t

2.2.2 Placer deposits

As stated before, the rare earth minerals in India mainly exist in the form of monazite distributed in placer deposits, coastal (shoreline) placers as well as inland placers. Just as in Brazil, placer deposits used to be the first deposits to be mined for REEs within India. As of this moment there are four mineral placer deposits being mined on a commercial scale by IREL. All these placer deposits are producing monazite sands. These deposits will be covered below. The other deposits are briefly summarized in Appendix A.

Aluva

The Aluva deposit is a placer deposit located in the province of Kerala. It is a monazite producer which also contains the heavy minerals titanium and zircon. The total reserves have been estimated on 150 Mt at 4% grade heavy minerals and 43.000 t monazite (Roskill, 1988).

Figure 2.2.3 shows the location of the Aluva deposit.

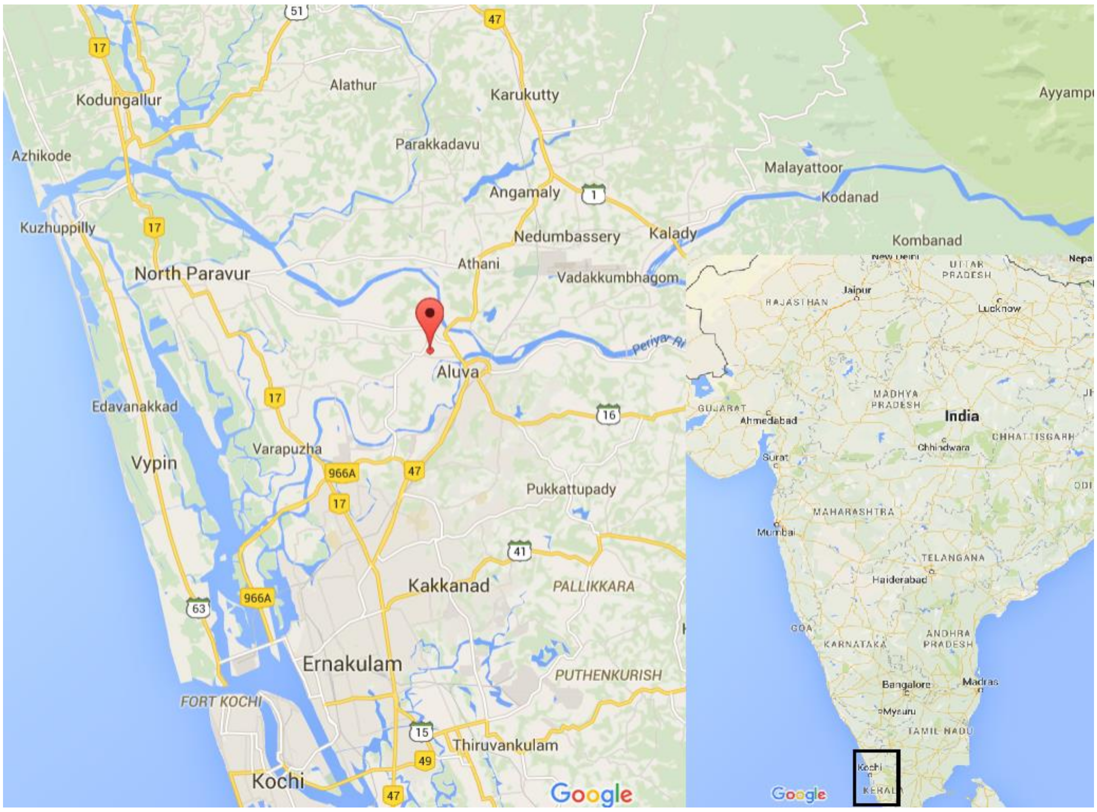

Fig. 2.2.3: *Location of the Aluva deposit. Modified after Google Maps (2016)*

The IREL rare earths division (RED) chemically treats the monazite to separate and upgrade its rare earths in composite chloride form. The plant was made operational way back in 1952 to take on a processing of 1400 t monazite every year. The capacity of the plant now is 3600 t per year. In addition to this, elaborate solvent extraction and ion exchange facilities have been built to produce the individual REOs like Ce, Nd, Pr and La. The RED has built up a large stockpile of impure thorium hydroxide upgrade associated with rare earths and unreacted materials. From now on RED treats this hydroxide upgrade rather than fresh monazite to convert the thorium into pure oxalate and REOs as two major fractions: Ce oxide- and Ce oxide-free rare earth chlorides (IREL, 2016).

Chavara

Within the province of Kerala, 10 km north of Kollam lays a deposit which contains a large variety of ore minerals. This is the Chavara (previously called Quilon) deposit. The mine contains 40% heavy minerals and extends over a length of 23 kilometers in the belt of Neendakara and Kayamkulam and dates from the Quaternary.
Figure 2.2.4 shows the location of the Chavara deposit.

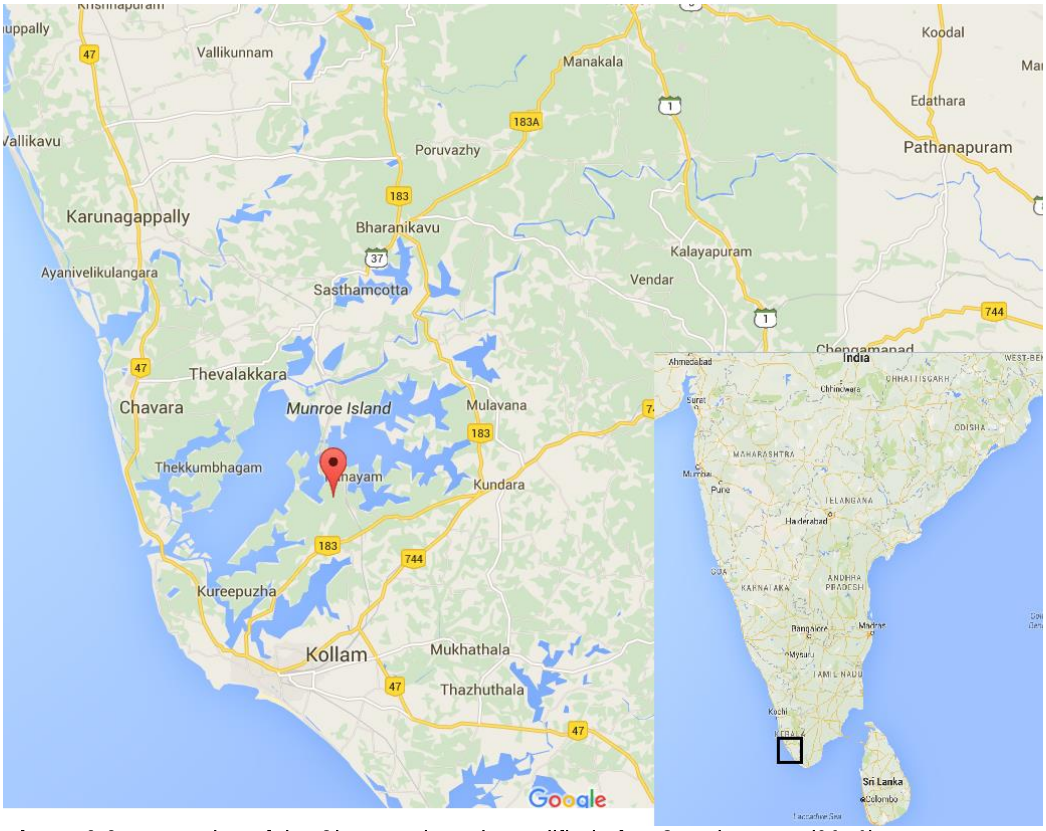

Figure 2.2.4: *Location of the Chavara deposit. Modified after Google Maps (2016)*

The initial product of the mine is Titanium. Monazite is just a byproduct, along with some other minerals. The total REE content of the deposit is 0.12 Mt monazite: ranging in grade from 0.5% to 1% and 118 Mt of monazite with a grade of 0.16% (Roskill, 1988; Jackson & Christiansen, 1993). Other than this, the deposit is quite rich with respect to ilmenite, rutile and zircon. The ilmenite is of a weathered variety containing 60% TiO_3 (IREL, 2016). Within the deposit, some leucoxene, sillimanite and garnet can be found as well.

The current annual production capacity of the IREL Chavara unit for wet, as well as dry mining and mineral separation (dredging/ up-gradation) is shown in table 2.5.

Table 2.5: *Annual production capacity of the IREL Chavara unit, India (IREL,2016).*

Name Mineral	Total Tonnage
Ilmenite	154.000 t
Rutile	9.500 t
Zircon	14.000 t
Sillimanite	7.000 t
Additional ground Zircon production	-
Zirflor (45 micron)	6.000 t
Microzir (1-3 micron)	500 t

Manavalakurichi

Another significant placer deposit owned by IREL is the Manavalakurichi deposit (Quaternary) which can be found in Tamil Nadu, just some 25 kilometers north from Kanyakumari, which is the southernmost tip of the Indian sub-continent.
Figure 2.2.5 shows the location of the Manavalakurichi deposit.

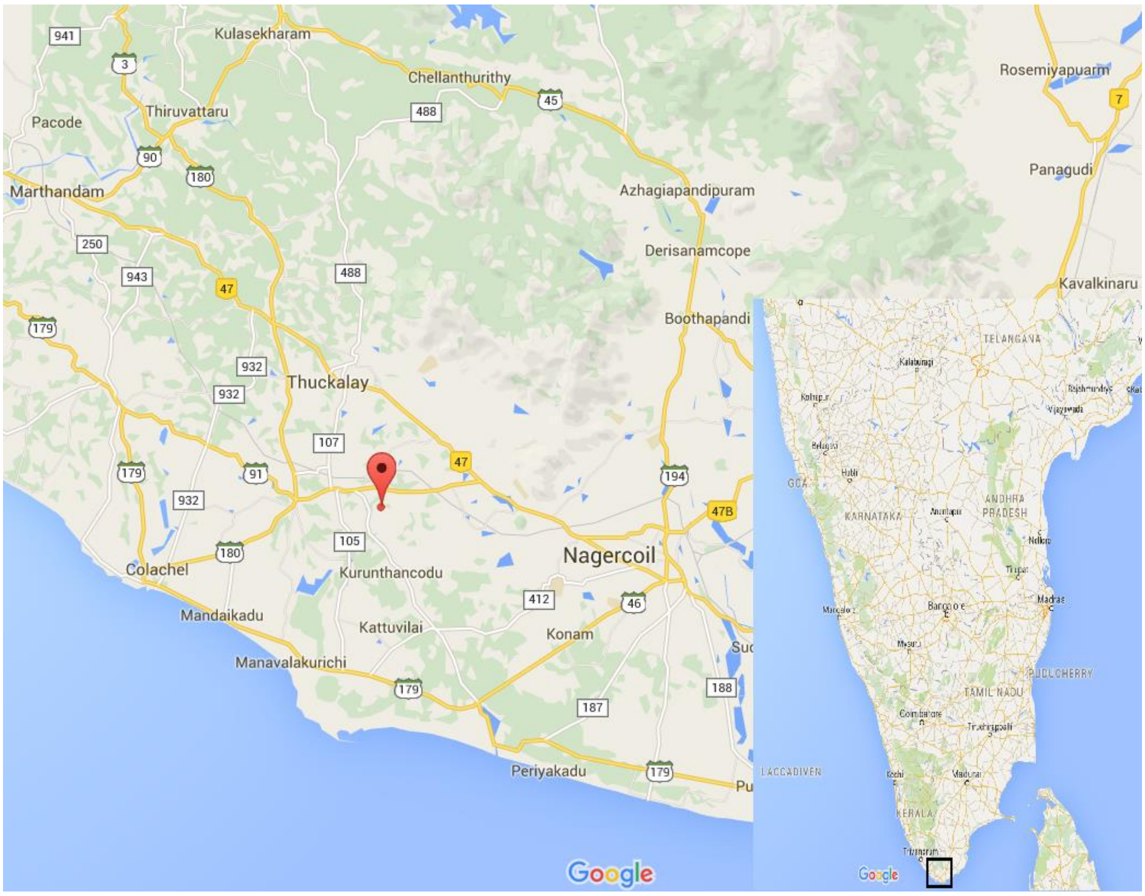

Figure 2.2.5: *Location of the Manavalakurichi deposit. Modified after Google Maps (2016)*

Just as with the Chavara deposit, the IREL facility over here is mainly a TiO_x producer (weathered ilmenite with 55% TiO_3 grade). However, the deposit is also producing monazite, rutile, zircon and garnet as byproducts (IREL, 2016). The estimated resource before producing of the Manavalakurichi deposit is 103.7 Mt monazite grading 2.5% (Jackson & Christiansen, 1993). Interesting fact to know is that this deposit was discovered in 1909 and first worked in 1911, making it one of the first worked REE deposit worldwide (Orris & Grauch, 2002)

The current annual production capacity of the IREL Manavalakurichi unit is shown in table 2.6.

Table 2.6: *Annual production capacity of the IREL Manavalakurichi unit, India (IREL,2016).*

Name Mineral	Total Tonnage
Monazite	3000 t
Ilmenite	90.000 t
Rutile	3500 t
Zircon	10.000 t
Garnet	10.000 t

Chatrapur

The fourth and final considerable REE-bearing mineral deposit in India, again mined by IREL is located in the province of Orissa and is also often referred to as OSCOM (Orissa Sands Complex). This placer deposit dates from the Quaternary and has quite a large mining area (24.64 km^2). This area is due to a belt of sand dunes, 1500 meters wide and 19 kilometers long (IREL, 2016).

Figure 2.2.6 shows the location of the Chatrapur (OSCOM) deposit.

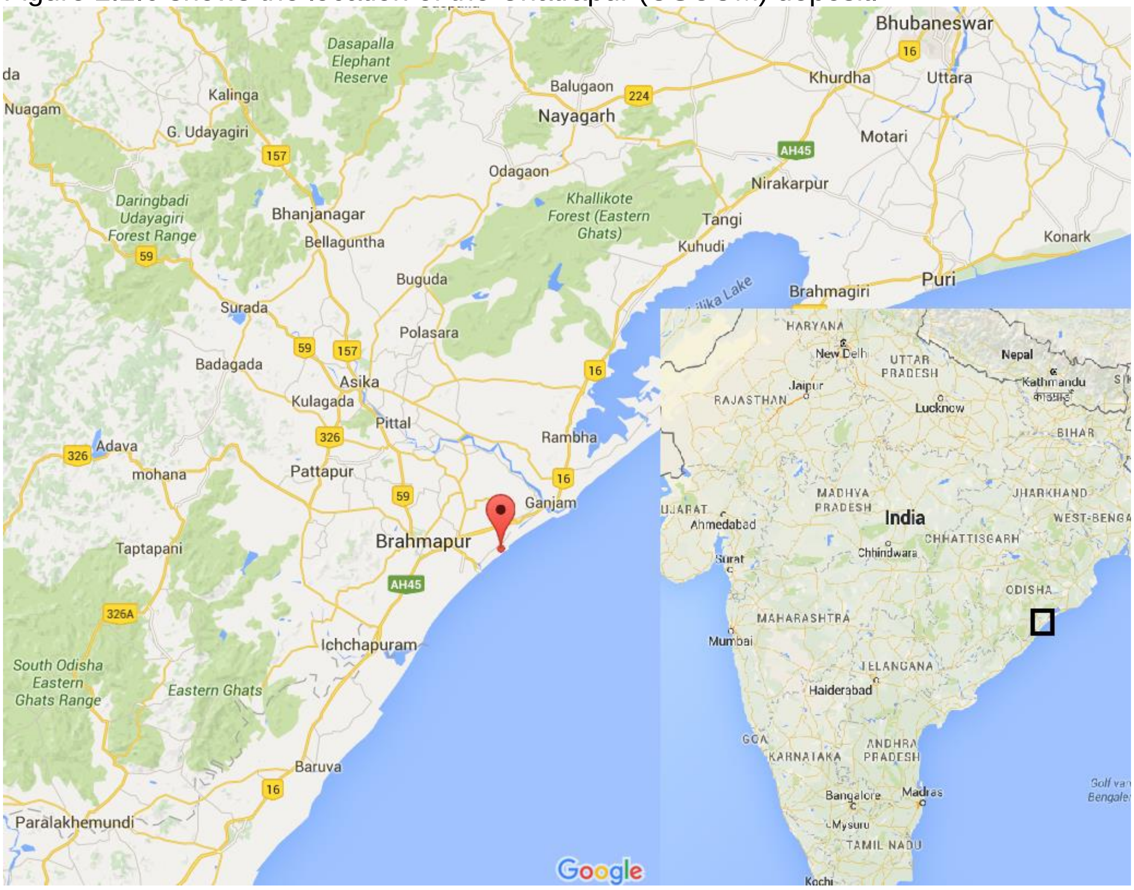

Figure 2.2.6: *Location of the Chatrapur deposit. Modified after Google Maps (2016)*

The primary product of the operation is Ilmenite with a 50% TiO_3 content. The plant was commissioned to produce 220.000 ton ilmenite per year. Other minerals that are being produced as a byproduct include rutile, leucoxene, zircon, kyanite, garnet, sillimanite and of course monazite (Orris & Grauch, 2002). The proven resources of the OSCOM are 224 Mt ore, of which:

- 0.632% monazite
- 9.6% ilmenite
- 0.5% rutile
- 0.42% zircon
- 3.29% sillimanite

(Jackson & Christiansen, 1993)

Besides these four main placer deposits in India, there are some other significant (partly past/ partly depleted) placer deposits containing (initial) notable amounts of rare earth elements. But for the sake of the length of this report they are not elaborately discussed. Nevertheless they are briefly displayed and/or discussed in appendix A. Table 2.7 shows the estimated monazite resources for the placer deposits that are currently being exploited by IREL.

	Table 2.7: *Estimation of REE mineralization within the 'main' placer deposits in India.*		
Name	**Total REE_2O_3 (ore grade)**	**Main REE carrying minerals**	**Other Mineralization**
Aluva	43.000 t (?)	monazite	titanium, zircon
Chavara (Quilon)	120.000 t (0.5-1%) 118 Mt (0.16%)	monazite	ilmenite, rutile, zircon, leucoxene, sillimanite, garnet
Manavalakurichi	103.7 Mt (2.5%)	monazite	ilmenite, rutile, zircon, garnet, sillimanite, baddeleyite
Chatrapur	240 Mt (0.632%)	monazite	ilmenite, rutile, leucoxene, zircon, kyanite, garnet, sillimanite
Total	461.6 Mt (ranging 0.16-2.5%)	-	-

3
Discussion

Writing this report raised a few questions and may evoke discussion considering some aspects of the REE industry. One of them is the limited and/or outdated amount of information available on (potentially interesting) REE-bearing deposits. A lot of information is limited due to the fact that (at that time) the deposit has not been considered interesting enough to investigate further or for a detailed feasibility study. A considerable amount of articles used within the resource estimations, especially for the deposits and occurrences which are only noted in the Appendix and not in the report itself are dated 1980s-1990s. Luckily, with the increasing interest for the application of REEs, more known, as well as new resources are being (re)studied which may result in all sorts of new reports and articles.

Another aspect on this matter is the fact that for the Brazilian deposits a lot of valuable articles and reports are written in Portuguese. Some aspects of these Portuguese articles were translated with the use of Google translate. Some other Portuguese articles were used as references in other English papers and reports and therefore also noticed in the references section below.

An aspect which has effect on the recent western REE industry, and for that matter the whole mining industry, is the environmental regulation within China, with China being currently the leading REE producer worldwide. Generally speaking, the environmental regulations within China are looser applied than in the rest of the world, which means they can save money on not investing in environmental-friendly applications and innovations which results in the fact that it becomes even harder for other countries to compete.

Considering other legislation problems one finds the topic of the storage and disposal of radioactive waste which has to be taken into account with the processing of xenotime and monazite. This was already briefly discussed with the example of Lynas Corporation in the introduction. Xenotime, which is mainly carrying the HREE Yttrium, is on one hand a great host of HREEs which are amongst the most critical elements, but on the other hand, mining more xenotime will result in more radioactive thorium and uranium which has to be disposed of. Publicly, the topic of radioactive waste also sparks a lot of buzz and debates. There even has been set up a website to stop Lynas Corporation (stoplynas.org, 2016).

Furthermore, we can consider the future of REE-mining to be blooming as long as the demand for modern technology in which these REEs are being used will increase. However the fact that LREEs are way more abundant (about 75% of total production) than HREEs can pose problems in the (near) future, as these HREEs are also used in a diverse range of high-tech applications from aerospace communication devices to nuclear magnetic resonance scanning (Santana et al., 2015). The scarcity of these HREEs may pose some uncertainty in the current industry, but on the other hand, the increase in demand and therefore price, may evoke exploration of new resources and stimulate potentiality of currently non-feasible deposits.

These remarks pose a lot of challenges for the future; How to tackle the lax environmental laws in China? How to cope with radioactive materials? And lastly, how does the REE industry develops over the years?

4
CONCLUSIONS

Summing up this report, we find that the REE reserves for Brazil are estimated at 22 Mt, which is around 20% of the world total (USGS, 2016). This puts Brazil in second place, just behind China. Resource estimation for REOs in Brazil point out that close to 53 Mt is present in the current known deposits (Chen, 2011). This is over 32% of the world's total REE resource, whereas China is estimated to host 22% of world's total REE resource. These estimations suggest that Brazil might surpass China in the future and rank as first in rare earth deposits production. However, the production of REEs in Brazil is fairly low at the moment (140 tons/year in 2013) (Mining-Technology, 2014). Yet, the potentiality is there. For example if we look at the new projects which have been started up during the last few years in Brazil (the Araxá project by MBAC Fertilizer Corp. and the Serra do Ramalho project by World Mineral Resources (WMR)). For Brazil, the main host deposits are the carbonatites and granitic deposits. There are also considerable amounts of monazite found in placer deposits.

India on the other hand has an estimated REE reserve of 3.1 Mt, which is around 2.2% of the world total (USGS, 2016). The total REE resources for India are considerably lower than for Brazil or China for that matter (Chen, 2011). The REE production in India nonetheless, is considerably larger than in Brazil. This production stands at 2.900 tons/year in 2013, which is 2.6% of the global REE production (Mining-Technology, 2014). This larger production is due to the fact that these REEs are situated within placer deposits, which are considerably easier mined than carbonatite or granitic deposits. Also the fact that these deposits are mined for titanium is very important. REEs are essentially just a byproduct at the IREL mining sites in India. The potentiality for the REE mining industry in India is smaller due to the fact that there are simply fewer known resources and reserves.

Generally speaking REEs are being mined as byproducts, mainly because deposits and/or their concentrations are just not large enough. Also, LREEs are more abundant (75% of total REE) than HREEs. So the potentiality for a mine with HREEs as main producer is greater as these elements are more critical than the LREEs. These HREEs are often found in deposits associated with granitic rocks… although these granitic rocks usually do not form large primary deposits like the Pitinga deposit (Takehara et al., 2014). This criticalness of HREE might pose a challenge in the future, if findings of new HREE deposits hold off.

Furthermore, the abundancy of the HREEs is not the only challenge posed in the future. There is much fuss about environmental and radiological legislations. These concerns, which are caused by REE extraction, pose a challenge for the future mining industry and policy makers (Takehara et al., 2014).

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APPENDIX A

Appendix A: *REE-bearing mineral deposits within Brazil*. (mostly after Orris & Grauch, 2002)

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Carbonatite	Barra do Itapirapuã	São Paulo	44.8 Mt (0.7%)	Occurrence	Bastnaesite, ancylite, synchysite, parisite	Fluorite, galena, barite, strontianite, pyrochlore	Calcite, dolomite, melilite, quartz	Early Cretaceous	Carbonatite (sovitic), nepheline syenite, pulaskite	-	amazonite 6% REE in hematite mine. REE probably from hydrothermal solutions.
	Itanhaem	São Paulo	-	Occurrence	-	Thorium	-	129.5 Ma	Tinguaite dikes	-	REE was found in biotite tinguaite dikes.
	Mato Preto	Parana	-	Past Fluorite Producer; byproduct	-	fluorite, thorium, Phosphor, barite, galena, pyrochlore	-	65.6-67.0 Ma	ijolite, nepheline syenite, carbonatite, phonolite	-	Fluorite mine closed in 1999. High REE.

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
	Salitre I & II	Minas Gerais	-	Titanium resource, REE occurrence	Monazite, apatite, anatase, perovskiteomorphite	carbonate-fluorapatite, magnetite, titanite, apatite, zircon, uranium, thorium, niobium, ilmenite, pyrochlore, zeolite	cancrinite, zeolite, aegirine, aenigmatite calcite, biotite	82.7 ± 4.2 Ma	syenite, nepheline syenite, pyroxenite, trachyte, carbonatite	-	High REE.
Carbonatite with residual enrichment	Anitápolis	Santa Catarina	-	Phosphor producer, REE occurrence	Apatite	Apatite, magnetite	Pyroxene, biotite, phlogopite amphibole olivine	Early Cretaceous	-	-	-
	Araxá	Minas Gerais	22 Mt (3.02%)	Niobium-Phosphor producer, REE-Ba occurrence	monazite, gorceixite, goyazite, apatite, bariopyrochlore, calcite, ancylite, ceriopyrochlore	apatite, bariopyrochlore, barium, magnesium, gorceixite, ilmenite, hematite, gibbsite, bohmite, pandaite, pyrochlore, vermiculite, isokite.	dolomite, arfvedsonite, aegirine, augite, goetite, limonazite, kaolinite, quartz	87.2 ± 4.4 Ma	beforsite, glimmerite, sovite, pyroxenite	CBMM	Weathered carbonatite with 3 separate deposits. Barreiro Complex is circular and about 4.5 km in diameter. World's largest Nb reserve.
	Caiapo	Goiás	-	Occurrence	-	siderite, barite, rutileile, pyrochlore	dolomite, calcite, ankerite	Post-Devonian	carbonatite, carbonatitic breccia, ijolite, silexite, fenite	-	Anomalous Sr, Ba, REE in the lateritic cover.

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Carbonatite with residual enrichment	Catalão I	Goiás	119 Mt (5.5%)	Niobium-P producer; minor byproducer of REE (Ce); Ti resource	Ce-Ba-pyrochlore, gorceixite, apatite, monazite, florencite, ancylite, goyazite, anatase, rhabdophane	pyrochlore, apatite, vermiculite, perovskite, ilmenite, titanite, barite, hematite, magnetite, zircon, gibbsite, bohmite, goyazite, vivianite, hinsdalite, columbite	olivine, carbonate, amphibole, pyroxene, feldspar, nepheline, aegirine, quartz, kaolinite, goetite	4.2 Ma	pyroxenite, serpentinized peridotite, glimmerite	Mineração Catalão De Goiás S. A. (Mcg)	-
	Catalão II	Goiás	25 Mt (0.98%)	Niobium resource	REE phosphates	magnetite, pyrochlore, vermiculite, barite, Ba-pyrochlore	calcite, phlogopite, feldspar, amphibole	81.1 Ma	sovite, phoscorite, glimmerite	Mineração Catalão De Goiás S. A. (Mcg)	15 Km north of Catalão I.
	Maicuru	Pará	Laterite containing 17% REE	Occurrence	Monazite	apatite, anatase, titanium, chrome, vanadium	-	Proterozoic	laterite, ultrabasic alkaline intrusives with probably carbonatite	-	Intrusions covered by laterite.
	Maraconai	Pará	-	Occurrence	Monazite, anatase	Chrome, vanadium, zircon, nickel, tantalum	-	-	probably alkaline-ultrabasic intrusions	-	Exists of 2 intrusions.

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Carbonatite with residual enrichment	Morro Dos Seis Lagos	Amazonas	43.5 Mt (1.5%)	Occurrence,	Monazite, florencite, rhabdophane, romanchite group, pyrochlore	Apatite, fluorite, titanite	nepheline, cancrinite, aegirine, epidote	Late Cretaceous	nepheline syenite, weathered carbonatite	-	Most of intrusion lies in Guyana.
	Serra Negra	Minas Gerais	200 Mt (27.7% Ti_2) from which the Ti concentrates contain >3% REE	Titanium resource with potential byproduct REE	Apatite, anatase	Anatase, Thorium, Uranium, Pyrochole	-	Cretaceous	weathered carbonatite, peridotite, dunite, shonkinite, jacupirangite	-	High LREE/HREE ratio.
	Arenopolis	Goías	-	Occurrence	Baddeleyite, eudidymite		albite, orthoclase, nepheline, aegirine, analcime, biotite, cancrinite, zeolite, olivine, pyroxene	Cretaceous	alkali metagabbro, ijolite, melteigite, pyroxenite, nepheline syenite, foyaite, laterite	-	Rare earths are concentrated in dikes within the syenite
	Jacupiranga	São Paulo	-	Phosphor-Lime producer; REE Occurrence	Apatite	magnetite, apatite, garnierite, pyrite, pyrrhotite, galena, ilmenite, pyrochlore, baddeleyite, barite, perovskite, clinohumite	calcite, dolomite, phlogopite, olivine, serpentine	125 – 161 Ma	pyroxenite, jacupirangite, ijolite, nepheline syenite, fenite	-	-
								1026 ± 28 Ma	nepheline syenite	-	-

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Carbonatite with residual enrichment	Mutum	Para	-	Occurrence	REE Phosphates	Titanite, apatite, fluorite	aegirine, cancrinite, nepheline, carbonate, epidote				
	Poços de Caldas	Minas Gerais, São Paulo	7.0 Mt (2,89%)	Past Uranium, Zircon & Bauxite producer	allanite, bastnaesite, eudidymite, cerianite	Thorium, U-baddeleyite, zircon, caldasite, thorogummite, magnetite, fluorite, astrophyllite lavenite, rosenbuschite, gibbsite	natrolite, cancrinite, nepheline kaolinite	86.3 Ma	highly weathered lujavrite and khibinite, nepheline syenite, phonolite; bauxite		Eudialyte contents range from 0 to 11% in the relatively small host bodies. Was once one of world's biggest baddeleyite deposits, but now nearly depleted. Weathered magnetite stock work in alkaline rocks.
Granitic	Pitinga	Amazonas	2 Mt (1.0%)	Byproduct	Monazite, xenotime, gargarinite, fluorecite, Yttrium-Niobium	cassiterite, zircon, pyrochlore, columbite, tantalite	-	1.82 Ga	-	Mineração Taboca S.A.	Greisenization of biotite granite produced primary mineralization. weathered zone with associated placers

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Granitic	Serra Dourada	Goiás	412 Mt (0.16%)	Byproduct	monazite, xenotime, zircon, allanite, apatite, bastnaesite, fluocerite	Niobium	-	2.84 Ga	-	Mata Azul, Serra Verde Mining	North and South part. See chapter 2.1.2.
Placer Deposits	Alcobaca	Bahia	?? Mt (0.47%)	Past byproduct	Monazite	Ilmenite, zircon, rutile, titanite	Quartz	Late Tertiary or Pleistocene-Holocene	dune and beach sand	Nuclebrás de Monazita e Associados Ltda	Marine Placers
	Anchieta	Espirito Santo	698 t (60.02 %) 57.000 t (0.71%)	(mostly) Depleted	Monazite	Ilmenite, rutile, zircon	Quartz	Late Tertiary	Barreira group and younger sediments	Nuclebrás de Monazita e Associados Ltda	Small modern beach placers, elevated bars. Monazite contains about 5.2% ThO2.
	Aracruz	Espirito Santo	2964 t (59.98%) 0.282 Mt (1.05%)	Past byproduct	Monazite	Ilmenite, rutile, zircon	Quartz	Late Tertiary	Barreira group	Nuclebrás de Monazita e Associados Ltda	-
	Brejo Grande	Sergipe	0.062 Mt monazite (?? %)	-	Monazite	Ilmenite, zircon	Quartz	Quaternary-Holocene	Sediments	-	-
	Buena	Rio de Janeiro	?? Mt (0.83%)	Byproduct	Monazite	Ilmenite, zircon, rutile	Quartz	Late Tertiary	Dune and beach sands	Indústrias Nucleares do Brasil SA (INB)	-
	Camaratuba	Rio Grande do Norte	4.7 Mt (0.55%)	-	Monazite, xenotime	Ilmenite, rutile, zircon, garnet	Tourmaline, Quartz	Late Tertiary	Dune sands	-	-

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Placer Deposits	Guarapari	Espirito Santo	950 t (60.04%)	Byproduct	Monazite	Ilmenite, zircon, rutile, magnetite	Quartz	Quaternary	Barreira group and younger sediments	Nuclebras de Monazita Associados Ltda.	-
	Itapemirim	Espirito Santo	-	Byproduct	Monazite	Ilmenite, zircon, Thorium	-	Tertiary	Barreira group and younger sediments	Nuclebras de Monazita Associados Ltda.	ThO2 content of monazite 5-12%. In Sao Joao da Barra region.
	Mataraca	Paraiba	-	Prospect	Monazite	Ilmenite, zircon, rutile, garnet, tourmaline	Quartz	Pleistocene – Holocene	Sediments	-	Marine Placer
	Northeast Dunes	-	145 Mt (0.033%)	Prospect	Monazite	Ilmenite, rutile, zircon	Quartz	-	Dune sands	-	-
	Paranagua	Parana	55 t (1.81%)	Reserves	Monazite	-	-	-	-	-	-
	Porto Seguro District	Bahia	-	Past byproduct	Monazite	Ilmenite, zircon	Quartz	-		Nuclebras de Monazita Associados Ltda.	Monazite contains >9% ThO_2.
	Prado Area	Bahia	4564 t (19.98%)	Byproduct	Monazite, xenotime, allanite	Ilmenite, zircon, spinel, garnet, thorite	Quartz, staurolite, kyanite	Recent	Beach sands	Nuclebras de Monazita Associados Ltda.	

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Placer Deposits	São João da Barra	Rio de Janeiro	8177 t (59.99%)	Byproduct	Monazite	Ilmenite, zircon	-	Tertiary – Quaternary	Barreira group and younger sediments-beach sand	Nuclebras de Monazita e Associados Ltda.	-
	Serra Jacareipe	Espirito Santo	0.0436 Mt (0.80%)	Occurrence	Monazite	Ilmenite, zircon, rutile	Quartz	Late Tertiary – Holocene	Dune and beach sands	-	Placers associated with veins, stockwork in gneiss
	São Gonçalo do Sapucai	Minas Gerais	28 million m3 (0.066%)	Under development (1989)	Monazite	Ilmenite, augite, zircon, garnet	-	Cenozoic	Fluvial sands	SA Mineração da Trinidade	Sands contain 0.66% monazite.
Placer Deposits with Uncertain origin	Careacu	Minas Gerais	2500 t (?? %)	Occurrence	Monazite	-	-	-	-	-	-
	Cordislandia	Minas Gerais	8200 t (?? %)	Occurrence	Monazite	-	-	-	-	-	-
	São Sebastio da Bela Vista	Minas Gerais	4100 t (?? %)	Occurrence	Monazite	-	-	-	-	-	-

Appendix B

Appendix B: *REE-bearing mineral deposits within India.* (mostly after Orris & Grauch, 2002)

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Carbonatite	Saranu	Rajasthan	≥5.5 % REO	Occurrence	carbocers	Strontianite	Calcite	-	Carbonatite dykes	-	Dikes are about 10 cm wide.
	Kamthai	Rajasthan	4.91 Mt (ranging from 3.33-17.31% in LREEs)	Recent Prospect	Bastnaesite (La-Ce), synchysite (Ce), carbocernaite (Ce), verianite (Ce)	Gallium, Germanium, Strontium-Oxide	Calcite	-	Carbonatite	-	Big carbonatite plug, some dykes, sills and veins.
Shoreline Placer Deposit	Aluva	Kerala	43.000 t (?? %)	Byproduct	Monazite	Titanium, zircon	-	Recent		Indian Rare Earths Limited	-
	Chatrapur (OSCOM)	Orissa	240 Mt (0.632%)	Byproduct	Monazite	Ilmenite, rutile, leucoxene, zircon, kyanite, garnet sillimanite	Quartz, staurolite, amphibole,	Quaternary	Sand dunes	Indian Rare Earths Limited	Byproduct of Ti mining. Belt of sand dunes in 1500 m wide and 19 km long. Relatively

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Shoreline Placer Deposit	Chavara (Quilon)	Kerala	0.12 Mt (0.5-1%) 118 Mt (0.16%)	Byproduct	Monazite	ilmenite, rutile, zircon, leucoxene, sillimanite, garnet	Quartz	Quaternary	Beach sand	Indian Rare Earths Limited	Byproduct of Titanium mining. Monazite distribution is patchy. Ore is 18% heavy minerals.
	Coleroon – Sirkazhi	Tamil Nadu/ Thanjavur	-	Occurrence	Monazite	Ilmenite, zircon, garnet	-	-	-	-	Deposits stretch 14 km from Coleroon River mouth to Sirkazhi.
	Kudiraimozhi	Tamil Nadu	370 Mt (8.9%)	Potential Resource	Monazite	Ilmenite, rutile, zircon, garnet, sillimanite, baddeleyite	-	-	-	-	-
	Manavalakurichi	Tamil Nadu/ Kanyakumari	103.7 Mt (2.5 %)	Byproduct	Monazite	Ilmenite, rutile, zircon, garnet, sillimanite, baddeleyite	Quartz	Quaternary	-	Indian Rare Earths Limited	Byproduct of Ti mining. Monazite discovered in 1909 and first worked in 1911.
	Palghat	Kerala/ Palghat	-	Occurrence	Monazite	Zircon	-	-	-	-	-
	Puri	Orissa/ Puri	-	Occurrence	Monazite	Ilmenite	-	-	-	-	-
	Trivandrum	Kerala	-	Occurrence	Monazite	-	-	-	-	-	-

Type Rock	Deposit name /District	State	Resource Tonnage and Grade	Status	REE Mineralogy	Other Ore & Significant Minerals	Gangue & Rock Forming Minerals	Age	Host rock(s)	Company	Comments
Shoreline Placer Deposit	Panchi-Purulia	Bihar	86.5 Mt (0.31 %)	Past Byproduct	Monazite	Ilmenite, rutile, zircon, apatite, columbite, magnetite	Quartz	Quaternary	Sand	-	Byproduct of titanium mining
Placer Deposits with uncertain origin	Bangalore	Mysore/ Bangalore	-	Occurrence	Monazite	-	-	-	-	-	-
	Gaya	Bihar/ Gaya	-	Occurrence	Monazite	-	-	-	-	-	
	Hazaribagh	Bihar/ Hazaribagh	-	Occurrence	Monazite	Zircon	-	-	--	-	-
	Koraput	Orissa/ Korapu	-	Occurrence	Monazite	Zircon	-	-	-	-	-
	Sabarkantha	Gujarat/ Sabarkantha	-	Occurrence	Monazite	-	-	-	-	-	-
	Visakhapatnam	Andhra Pradesh	-	Occurrence	Monazite	Ilmenite, zircon	-	-	-	-	-