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Thorium Resources as Co- and By-products of Rare Earth Deposits

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2019

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Printed by the IAEA in Austria
December 2019

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Thorium resources as co- and by-products of rare earth deposits / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2019. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1892 | Includes bibliographical references.
Identifiers: IAEAL 19-01284 | ISBN 978–92–0–163319–4 (paperback : alk. paper) | ISBN 978–92–0–163419–1 (pdf)
Subjects: LCSH: Thorium ores. | Rare earths. | Nuclear fuels.

FOREWORD

Increased demand for carbon-free energy and accelerated growth of global nuclear power make it possible that thorium will be used as a nuclear fuel in the future. Full commercialization of nuclear power based on thorium is yet to materialize because pilot test reactors and projects intended to appraise thorium have not yet found it to be a feasible reactor fuel. Government supported research projects have recently focused on the development of thorium fuelled nuclear power.

Some of the advantages of thorium as a nuclear fuel source include its abundance in the Earth's crust (6–10 g/t, making it 3–4 times more abundant than uranium) and the fact that most significant thorium deposits contain other valuable minerals such as niobium, rare earth elements, tantalum and/or titanium. Moreover, the types of waste product from spent fuel based on thorium fission are not useful for nuclear weapons (in contrast to plutonium, which is a by-product of nuclear power generation using uranium), and fuels based on thorium are efficient for reducing current plutonium stocks in that the fission chain reaction can be initiated using plutonium.

This publication provides an overview of thorium production as by-product production, including exploration, resource assessment, mining and processing, markets and economics (of the main product rare earth elements). It describes good practices in exploration, evaluation and production, and discusses issues relating to health, safety and environment, as well as waste management and mine closure. Other topics covered include storage of thorium products; policy, regulation and governance, social acceptance and stakeholder communications; and classification and management of projects with respect to application of United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009. It also presents case studies of major projects in production and committed projects.

The IAEA gratefully acknowledges the contributions of the experts who participated in the consultancy meetings for the planning and editing of this publication, and in particular the contributions of the late R. Villas-Boas (Brazil). The IAEA officers responsible for this publication were M. Fairclough and H. Tulsidas of the Division of Nuclear Fuel Cycle and Waste Technology.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Thorium and uranium can both be used as nuclear fuels. Interest in the use of thorium as a source of nuclear fuel has re-emerged in early 21st century [1]. Full commercialization of nuclear power based on thorium is yet to materialize because pilot test reactors and projects intended to appraise thorium have not yet found it a feasible reactor fuel. Several decades of research in various countries have demonstrated that designing a thorium-based nuclear reactor will take about as long as the history of reactors fuelled by uranium–plutonium i.e many decades. For comparison with thorium fuel cycles, the various concepts for advanced uranium reactors currently being researched and developed include:

- High temperature gas-cooled reactors (HTGRs);
- Molten salt reactors (MSRs);
- CANDU-type reactors;
- Advanced heavy water reactors (AHWRs);
- Fast breeder reactors (FBRs).

Government supported projects have recently focused research towards the development of thorium-based nuclear power [2]. These projects build upon past pilot scale reactor projects in Canada, Germany, India, the United States of America and the United Kingdom. On the basis of current activities, it is expected that, in the not too distant future, thorium will be utilized as a reactor fuel.

The advantages of thorium as a source of nuclear fuel include:

- Thorium's average abundance (6–10 g/t) in the Earth's crust (it is 3–4 times more abundant than uranium);
- Most significant thorium deposits contain other valuable minerals; for example, niobium, rare earth elements (REE), tantalum and/or titanium;
- The types of waste product arising from thorium fission are not useful in nuclear weaponry (in contrast to plutonium, which is a by-product of nuclear power generation using uranium). Additionally, fuels based on thorium are efficient for reduction of current plutonium stocks whereby the fission chain reaction can be initiated using plutonium
- Thorium-rich spent fuels have fewer radioactive elements and have smaller mass, volume and half-life compared with traditional uranium-based nuclear wastes.

In the past, there were more non-nuclear applications for thorium compounds, especially in gas mantles in light bulbs (thorium oxide produces a bright light), welding electrodes, heat resistant ceramics (thorium oxide melting point 3300+°C), arc lamps, camera lenses (high refractive index glass), aerospace components and many other applications. Radiological concerns over the use of thorium has led to increased use of alternatives, which have adversely impacted demand for thorium. For example, in an industrial context, yttrium compounds have replaced thorium compounds in incandescent lamp mantles and a magnesium alloy containing lanthanides, yttrium and zirconium has replaced magnesium–thorium alloys in aerospace applications. However, thorium continues to be used in certain catalysts, high temperature ceramics and welding electrodes.

1.2. OBJECTIVE

Several papers have been published over the past few decades on the possible use of thorium in various reactor types. Thus, it is worthwhile analysing the supply situation for additional thorium generated as a by-product of commodities produced for non-nuclear purposes.

The objective of this study on thorium as a by-product of REE and rare metals is to provide insights on thorium resources related to various geological deposits, mainly those where thorium occurs associated with elements (co- or by-product) that are recovered for specific purposes. Those elements are mainly REE, used in various metallurgical applications, e.g. computer industry, mobile phones, aerospace, ceramics and alloys. The main potential application for thorium is as a nuclear fuel [2].

The purpose of this publication is to provide information on the natural occurrence of thorium, the geology of thorium and potential thorium resources. Further, the publication provides an overview of the exploration and evaluation of projects, including studies for project feasibility, principles of ore processing, as well as market and production scenarios. Selected examples of deposits containing thorium as a potential co-product or by-product are presented as case studies in six countries.

1.3. SCOPE

Topics that will be covered include:

- Overview of thorium production as by-product production, including exploration, resource assessment, mining and processing;
- Markets and economics (of the main product REE/rare metals);
- Good practices in exploration, evaluation and production;
- Health, safety and environment;
- Mine closure;
- Storage of thorium products;
- Policy, regulation and governance;
- Social acceptance and stakeholder communications (with case studies highlighting relative successes and failures);
- How projects can be classified and managed with application of the United Nations Framework Classification 2009 for mineral resources (UNFC-2009);
- Case studies of major projects in production/committed projects.

1.4. STRUCTURE

This document is structured as outlined in the table of contents. It provides information on the geology of deposits and their resources are described, focusing on thorium as a by-product of REE and, to a lesser extent, of rare metals. The principles of ore processing are described. Socioeconomic considerations are briefly presented. Finally, exploration and evaluation of thorium resources are presented with examples in six different countries.

2. GEOLOGY OF THORIUM

2.1. GEOCHEMICAL BEHAVIOUR

Thorium (radioactive, main isotope ^{232}Th) averages ~6–10 g/t in the continental crust, ranging from less than 1 g/t in ultrabasic rocks to around 15 g/t in granites [3]. Its total abundance is 3–4 times that of uranium [4, 5]. Thorium belongs to a group of elements that are unable to to be accommodated in the lattices of common rock-forming minerals (e.g. feldspar, pyroxene). Owing to its ionic radius of 1×10^{-7} mm, thorium enters minerals with cations of similar size, including oxides, silicates, phosphates and others [4, 5].

Such elements are referred to as high field strength elements (HFSE) because their oxidation state of more than 2 (high charge) and their small-to-medium sized ionic radii produce a high electric field (high field strength). In addition to thorium, HFSE also include hafnium, niobium, phosphorus, tantalum, REE, titanium, tungsten, scandium, uranium, yttrium and zirconium. When common silicate minerals crystallize, most of the REE, Th and other HFSE tend to persist in the co-existing melt. Continuous productions (crystal fractionation) concentrate REE and Th in the remaining melt until minerals rich in these elements crystallize from the magma. Besides ionic radius, partitioning of the REE, Th and other HFSE between a mineral and co-existing magma can also depend on pressure, temperature, magmatic convection, fluid composition and differences in mineral settling velocities [6-8]. Ensuing hydrothermal–metasomatic mineralization and (or) weathering processes can increase the concentrations of the REE, Th and other HFSE [9, 10]. Owing to their geochemical affinities, Th and the other HFSE occur together as anomalous concentrations in a variety of highly fractionated rock types, mainly carbonatites and alkaline igneous intrusive complexes and associated veins and/or dykes. A more comprehensive treatment of igneous (primary) thorium mineral deposits and those derived from their weathering and erosion (secondary) follows.

2.2. OVERVIEW OF THORIUM PROVINCES

Like many other economic commodities, such as gold, platinum and copper, thorium does not display a uniform distribution, and certain regions of the Earth's crust seem to be particularly enriched in HFSE. As an example, granitic and metamorphic rocks that were once parts of the Palaeozoic Gondwana supercontinent and which are now found in the Brazil Shield, southern and eastern Africa, Madagascar, southern India and Australia, are often enriched in thorium and other HFSE relative to world averages [11, 12]. Most representative rocks of this large thorium province, known as the Erlank anomaly (Fig. 1), are represented by the monazite-bearing khondalites, charnockites and leptynites of the Eastern Ghats metamorphic belt in Odisha state (formerly Orissa) in north-eastern India [13], and the charnockites of Namaqualand in western South Africa [11, 12]. Another metallogenic province may be that of the Appalachian Belt, south-eastern USA, where monazite occurs in sillimanite-bearing metamorphic rocks within the southern Blue Ridge and inner Piedmont regions [14, 15]. A spatial relationship with other regions at specific points in geological time remains uncertain.

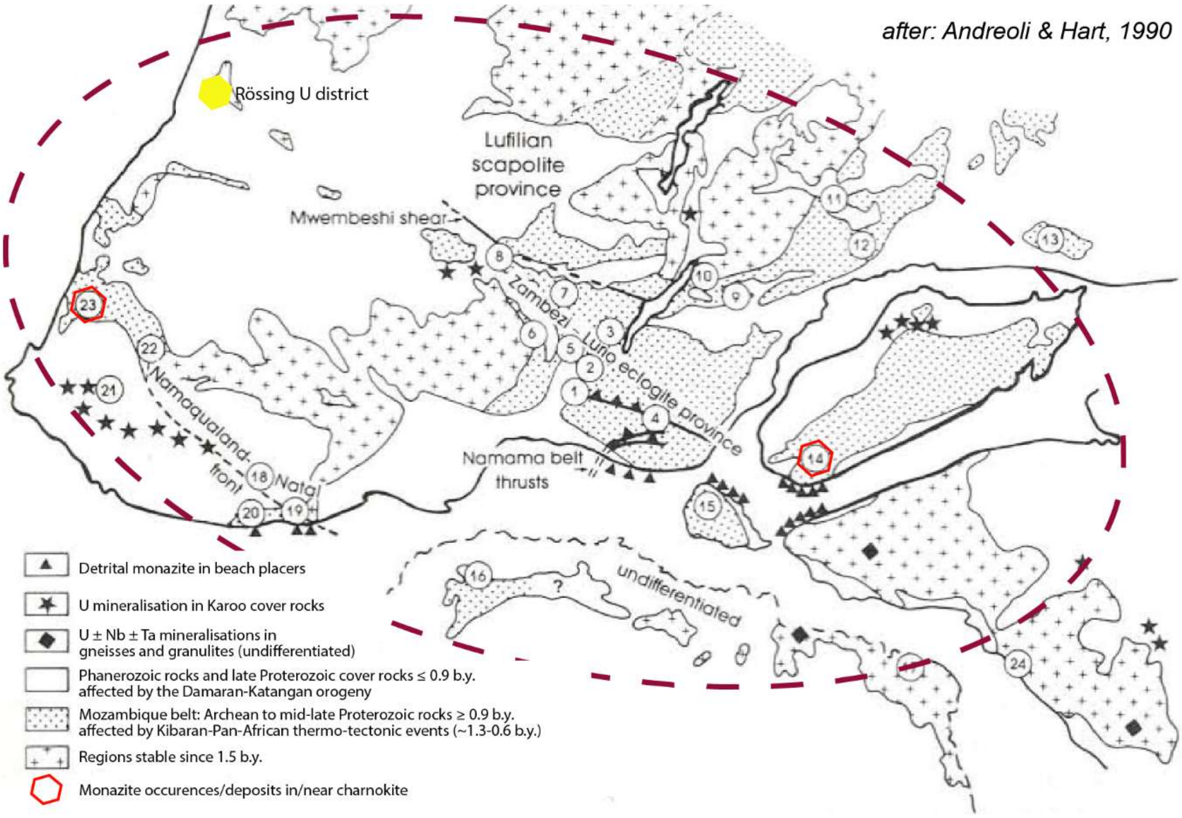

FIG. 1. Reconstructed Gondwana domain, known as the Erlank Anomaly, with Th, U, REE enriched granulites and high-grade gneisses (adapted from [11]).

Poorly defined thorium provinces may extend across the Fennoscandian Shield in northern Europe to Greenland and the Canadian Shield. Their positions during certain geological periods are shown in Fig. 2. Additionally, some areas of the Rocky Mountains in the USA, the Guiana Shield and other regions in South America, the West African Craton, and China have recorded thorium occurrences, mainly in carbonatites and alkaline rocks that show similarities.

Among the minerals rich in HFSE, monazite is particularly resistant to weathering and it is for this reason that it is found in many placer deposits (heavy mineral sands [16]). The primary global sources of REE (and Th) prior to 1965 were coastal deposits of HMS. This source was exceeded when large scale production of REE began at that time from the Mountain Pass carbonatite deposit in California, USA [17,18].

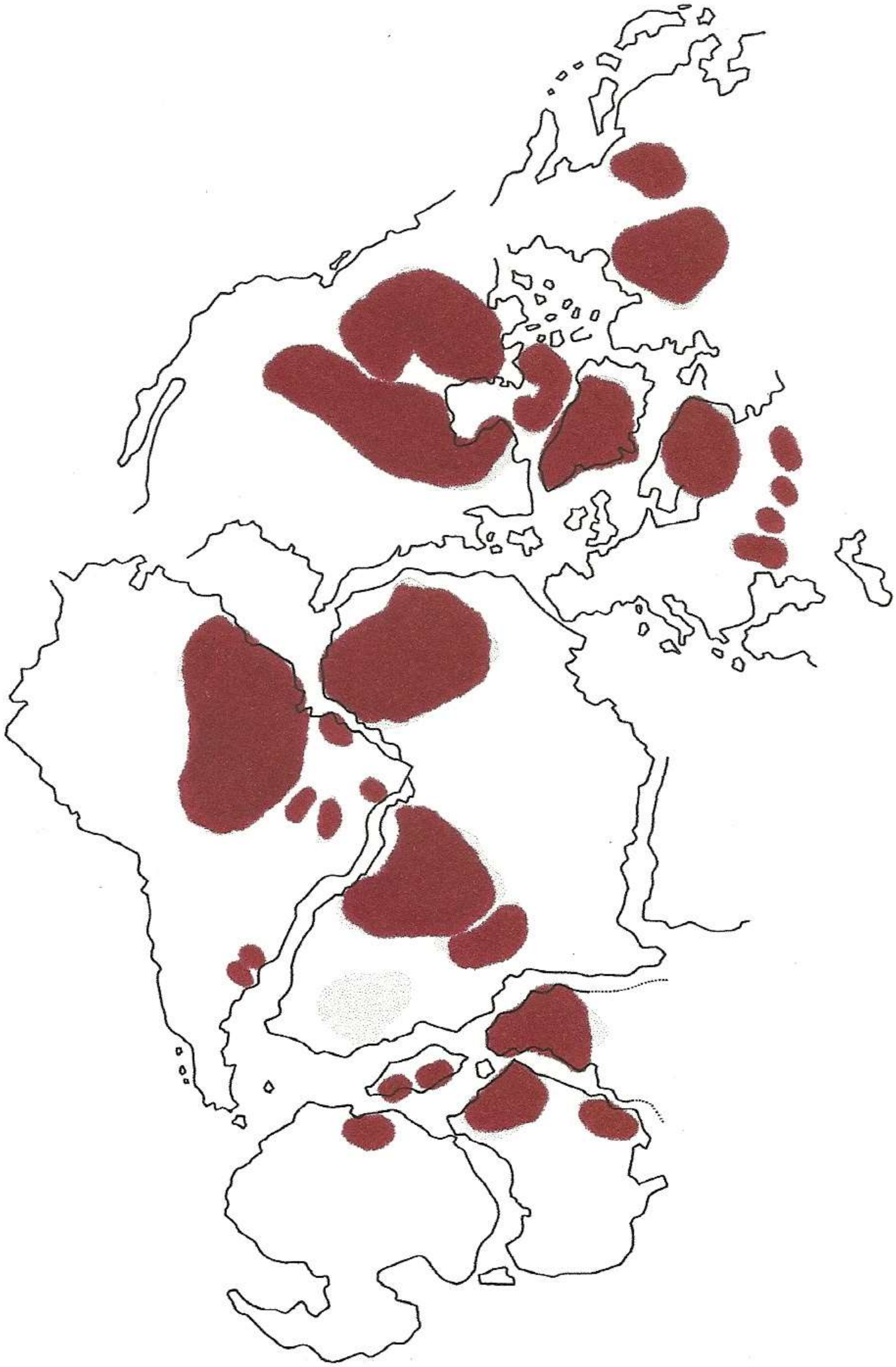

FIG. 2. Reconstruction of continents during Pangea (~250 Ma) (adapted from [19]). Coloured and stippled areas are shields older than 1.6 Ga. These shields are the main host of alkaline and carbonatitic magmatism and associated thorium enrichments. The magmatic associated mineralization is, however, much younger than the shields.

2.3. PRIMARY DEPOSITS OF THORIUM AND REE

2.3.1. Alkaline intrusions and igneous complexes

Shield areas of the continental crust are the preferential site of the alkaline igneous association. This is a rather unusual manifestation of igneous activity characterized by elevated concentrations of volatiles, alkalis and metals of related chemical behaviour, such as the large ion lithophile elements (Rb, Sr, Ba, etc.). Both ancient and modern regions of incipient fracturing and rifting of the continents are the prime setting for such intrusions; the East African Rift is a Late Cenozoic example of one such region. The HFSE group, especially REE, Y, Nb, Ta, Zr, U, Th, are frequently enriched in these rocks, with concentrations locally reaching economic grades that will allow mining. With respect to the geochemistry of Th and alkaline magmatism, some of the highest concentrations of monazite (and Th) exist in alkaline igneous intrusions (e.g. alkaline plutons, magmatic layered complexes and associated dykes and/or veins. However, despite the numerous publications dealing with rocks of alkaline character, details on thorium are often not available.

2.3.2. Carbonatites

Carbonatites are carbonate-rich igneous rocks formed by silica-deficient magmatic and related metasomatic processes in stable or extensional tectonic settings. The majority of carbonatites are composed of 50% or more of primary carbonate minerals (dolomite, calcite and/or ankerite). Genetically linked to alkaline syenitic plutons and related igneous rocks [20-23], over 400 carbonatites have been identified worldwide [24, 25]. A striking characteristic of carbonatites is their enrichment in volatiles (CO_2) and in HFSE, especially REE. The carbonatites may host REE deposits and associated enrichments in Th. Currently, only four typical carbonatite complexes are being mined for REE: the Mountain Pass deposit in California, USA, and the Weishan, Maoniuping and Daluxiang deposits in China [23]. The world class deposit of REE at Mountain Pass is estimated to contain ~17 Mt of carbonatite ore grading 8.0% rare earth oxides (REO) and ~4200 t Th [26, 27]. The deposit is owned and mined by Molycorp Inc. Only REE are recovered by the separation process at this operation and the company has no plans to recover thorium (see Case Studies: USA). The Phalaborwa carbonatite complex in South Africa is mined for copper and phosphate. By-product uranium has also been recovered. Thorium is disposed of in controlled tailings enclosures (see Case Studies: South Africa).

In Western Australia, the Mount Weld mine exploits the weathered REE-rich zone that overlies a carbonatite [25, 28]. This deposit hosts ~15 Mt of REE, with niobium (average ore grade: 0.9% Nb_2O_5), low grade tantalum (average ore grade: 0.034% Ta_2O_5) and thorium as possible by-products. The owner, Lynas Corp., has contracted to process the ore in Malaysia. Thorium enrichments are also associated with the largest niobium deposits. The Araxá carbonatite deposit in Minas Gerais, Brazil, is considered to be the world's largest known niobium deposit. Identified ore resources are reported as 440 Mt at an average grade of 2.5–3% Nb_2O_5. Pyrochlore is the principal ore mineral at Araxá [29]. The orebody is a deeply weathered laterite developed in the upper zones of a Nb–Ta-rich carbonatite. Supergene enrichment of the carbonatite has enhanced the Nb content, with Nb>Ta, whereas the underlying, non-weathered carbonatite contains ~1.5% Nb_2O_5.

The giant Bayan Obo deposit of China is not included here, even though it displays distinct carbonatite affinities. It is discussed under the category of deposits of uncertain origin.

2.3.3. Syenites and related rocks

Syenite magmas have sufficient silica to precipitate Na- and K-bearing minerals such as alkali feldspar and feldspathoids (i.e. nepheline), and to release fluids similarly enriched in alkali elements [30, 31]. Peralkaline rocks, defined by $Al_2O_3<(Na_2O+K_2O)$, typically have higher enrichments in REE than most other igneous rocks [23, 30-34]. With respect to the geochemistry of Th and alkaline magmatism, some of the highest concentrations of monazite (and Th) exist in alkaline igneous intrusions (e.g. alkaline plutons, magmatic layered complexes and associated dykes and/or veins). Owing to the co-occurrence of Th and REE, REE-enriched alkaline igneous rocks are also anomalous with respect to their Th contents. The Nechalacho deposit at Thor Lake in the Northwest Territories, Canada, is an example of a REE–Th-rich, layered peralkaline igneous complex [35]. The primary phase REE ore minerals are eudialyte and zircon. These minerals have crystallized and settled by gravity from the alkaline magma [35]. Multiple episodes of hydrothermal metasomatism dissolved these primary phases, depositing REE in fergusonite, allanite and bastnäsite, along with precipitation of REE and Th in late-stage zircon and monazite [35]. However, despite being one of the world's largest deposits of REE, Nb and Ta, scant information is available on its thorium resources (see Case Study: Canada).

Another well-developed example of a layered alkaline magmatic complex with enrichments in REE and Th is the Illimaussaq alkaline complex in southern Greenland [31]. The Kvanefjeld deposit is being evaluated for its REE, Zn and U resources [36]. The rocks hosting the REE–Zn–U–Th mineralization are rare forms of nepheline syenite. Monazite is amongst 200 minerals identified in the complex [31, 36]. Earlier estimates indicated a resource of 86 000–93 000 t Th. Recent studies by Greenland Minerals have mainly focused on non-radioactive minerals.

Estimates have been made for REE, Nb and Th in the alkali trachyte at Toongi, New South Wales, Australia. The deposit contains ~35 000 t Th at a grade of 0.0478% Th [3,37] and is hosted in an altered body in which the subsurface extension is only partially explored. The rocks (alkali trachytic lavas, tuffs and basic effusives) probably result from alkali magmatism of Mesozoic age [37].

2.3.4. Alkaline granites, pegmatites and vein-type deposits related to alkaline intrusions

Should excess silica be available in the magmas, then even alkaline and peralkaline granites, pegmatites and related lavas (pantellerite) might also occur, although not necessarily in the same stable shield areas mentioned above. Elevated Th levels can occur in REE–Li–Rb–Cs–Be–Sn–Ta–Nb-enriched granites and pegmatites (with Ta>Nb). These intrusions typically contain Ta-rich magmatic columbite and cassiterite [38]. Pegmatites of this deposit type are represented by the Yichun Ta–Nb–Li deposit, Jiangxi Province, in southern China [39] and by the Ta–Nb–Sn mineralization in the Nanping granitic pegmatite, Fujian, China [40], which once produced tantalum. No information is given for thorium.

At Ghurayyah, Saudi Arabia, peralkaline granites reportedly may contain one of the world largest potential resources of Ta–Nb–Zr–REE ores. However, no information is given for its thorium content [41]. The pegmatite at Abu Dabbab, in Egypt's Eastern Desert, is associated with calc-alkaline and peraluminous leucogranite, carries Ta, Sn and W [41] and possibly some thorium as well. At Nolan´s Bore (Northern Territory, Australia), a vein rich in REE, fluorapatite, uranium and thorium contains ~81 500 t Th in more than 30 Mt of ore (average grade: 0.27% Th, 2.8% REE). The owner plans to separate the thorium and store it at the mine site for possible future use [42] (see Case Study: Australia).

2.3.5. Charnockite–leucotonalite dykes

The type locality of a dyke-hosted monazite deposit is the dormant Steenkampskraal mine, Western Cape, South Africa (the world's leading thorium producer in the late 1950s and early 1960s). Originally considered a hydrothermal vein-type deposit, the orebody has been reinterpreted as being of igneous origin and associated with the tectonic and metamorphic evolution of the ~1030 Ma Namaqualand metamorphic complex [12, 43, 44]. The distinctive features are:

- Geometry: sheets and lenses, locally boudinaged geometry ranging in thickness between 0.02 m and >10 m, with an average thickness of 0.6 m;
- Mineralogy: massive, equigranular and fine-grained monazite and apatite rock with zircon, chalcopyrite, ilmenite and magnetite in variable proportions;
- Local ore variations: thorium occurs as disseminated monazite (6–7% Th) in a magnetite–apatite rich rock (nelsonite);
- Regional association: high temperature (~900ºC) metamorphic rocks (charnockite, granulite);
- Host to the ore: megacrystic to pegmatoidal alaskite, leucotonalite (very common), enderbite, charnockite and anorthosite. Charnockite is not always present and tonalite is often associated with the Steenkampskraal 'clan' of Th enriched ores. The rocks are non-alkaline in character, though small syenite-like accumulations may occur locally;
- Structural control: emplacement of the mineralized magma exploited tight fold and ductile shear zones in a granitic basement.

Charnockite–leucotonalite-hosted thorium mineralization also occurs scattered (with varying degrees of monazite enrichment) at many localities in the Namaqualand region of western South Africa [12, 13]. Monazite–apatite veins associated with charnockites have been reported in south-eastern Madagascar [11]. No definite explanation exists for the origin of the REE- and Th-rich melts, but field, geochemical and petrographic observations indicate that they are differentiates of unusual (Cu)–REE–Th-rich non-alkaline noritic to anorthositic intrusions [11, 45]. As such, these mafic magmas bear the distinctive signature of the Erlank thorium metallogenic province [13].

2.3.6. Massive iron oxide deposits of hydrothermal–magmatic origin

Massive iron oxide deposits of hydrothermal–magmatic origin can contain resources of Th in the accessory mineral fluorapatite. This association is typified by Th- and REE-bearing fluorapatite occurring within iron orebodies once mined in the Mineville iron district of northern New York, USA. The orebodies are folded and faulted magnetite deposits occurring within a complex suite of Precambrian igneous and metamorphic rocks [26, 46]. The iron deposit mineralogy comprises mainly magnetite, hematite and fluorine-rich apatite [46]. Iron deposits in the Mineville–Port Henry area contain fluorapatite, Th and REE. Average REO content of 11.14% in fluorapatite was found in the magnetite–hematite orebodies; U and Th contents averaging 0.032% and 0.15%, respectively, are reported [46].

2.3.7. High grade metasomatites

2.3.7.1. Na-metasomatites

Na-metasomatites are widely distributed in Precambrian regions [47] and collectively contain uranium. As an example, the phospho-uraniferous deposit of Itataia or Santa Quiteria/Ceara, north-east Brazil, is acknowledged as containing ~120 000 t of U. INB-Brazil in 2011 has planned investments of US$350 million and intends to produce 240 Mt of P_2O_5 and ~1300 t of U. This will be achieved by leaching the phosphate to produce a uranium depleted phosphoric acid. Part of the thorium goes into the precipitated phosphogypsum and part remains in the phosphoric acid liquor and requires further treatment to facilitate recovery.

2.3.7.2. Ca-metasomatites

An interesting type of uranium and thorium deposit has been reported from the Tranomaro area in southern Madagascar, where mica and uranothorianite have been mined in the past from pegmatoidal Ca-pyroxene–phlogopite–scapolite mineralization within high grade metamorphic rocks [4, 11].

2.3.8. Deposits of uncertain origin

2.3.8.1. Lemhi Pass district, Idaho–Montana border, USA

Most of the vein deposits of this district are thought to be related to alkaline magmatism. Thorite-bearing veins that comprise the Lemhi Pass district appear to contain the largest Th resource in the USA [26]. A total of 219 veins enriched in Th and REE have been mapped, ranging from 1 to 1.325 m in length and from a few centimetres to 12 m in width [46]. A total of 15 Th-bearing veins exceed 300 m in length. REE- and Th-bearing allanite and monazite are locally abundant. Analyses of 31 vein samples showed total REE contents averaging 0.43%, similar to the average Th oxide content of 0.43% in the 10 largest veins [48, 49].

2.3.8.2. Iron Hill, Colorado, USA

Thorium in significant amounts (25 000 t) has been reported from a large, low grade (38 ppm Th) carbonatite stock at Iron Hill, Colorado [50].

2.3.8.3. Bayan Obo deposit, China

The genesis of the Bayan Obo deposit remains controversial. At present, the deposit is interpreted both as carbonatite-related as well as a hydrothermal iron oxide–Cu–Au–REE (some researchers have suggested similarities to Olympic Dam) [51]. Likewise, the deposit is classified as polygenic. The main ore is iron, with resources of ~470 Mt. In addition, it also contains 130 Mt of fluorite, 1 Mt of Nb_2O_5 and more than 40 Mt of REE (3–5% REE), which brings the deposit into the world class category [52]. Bayan Obo contains about 70–80% of the world's estimated REE resources. Major REE minerals are bastnäsite (containing 0.02–0.28% Th) and monazite (0.26% Th) [52]. While not as highly concentrated in Th as other deposits [51], the scale of mining (~9 Mt of iron annually, plus recovery of REE and other metals) makes recovery of by-product thorium an option. Currently, thorium is not recovered and is discharged with tailings. No information is available as to whether studies have been undertaken to estimate thorium resources, although small amounts of thorium have been recovered for research purposes [53].

TABLE 1. EXAMPLES OF THORIUM RESOURCES AS A BY-PRODUCT IN PRIMARY DEPOSITS

Country	Type	Major commodities	Th resources (t)	Average Th grade in ore (%)
Australia				
Mt Weld [28]	Carbonatite	REE, Y, Th	~24 000	0.04–0.06
Toongi [37]	Alkaline trachyte	REE, U, Th	35 000	0.048
Nolans Bore [37]	Vein	REE, P, U, Th	53 000	0.286
Western Australia, various [3]	Various	REE, Nb, Ta, U, Zr	30 000	0.03–0.5
Brazil				
Araxá [29]	Carbonatite	Nb, Th	>400 000	0.09–0.13
Morro dos Seis Lagos [3]	Carbonatite	Nb, REE	?	?
Morro do Ferro (Pocos de Caldas) [3]	Peralkaline intrusion	U, REE	17 500 (30 700)	1–2 (0.44)
Pitinga [3]	Granitic intrusion	Nb, Ta, Sn	251 000	0.05–0.07
Catalão [29]	Alkaline intrusion	Nb	12 000	?
Canada				
Elliot Lake area [3]	Quartz pebble conglomerate	U, REE, Th	80 000 in existing tails	0.05
Thor Lake/Nechalacho [35]	Peralkaline intrusion	REE, Nb, Ta,	22 000	<0.020
Others [3]	Various	Various	Unknown	Unknown
China				
Bayan Obo [51]	Polygenic	Fe, REE, Nb, F, Th	?	0.26% in monazite 0.02–0.2% in bastnäsite
Greenland (Denmark)				
Illimaussaq [36]	Peralkaline intrusion	REE, F, Zn, U, Th	86 000–93 000	<0.1
Norway				
Fen [3]	Carbonatite	Nb, Th	~87 000	0.5–2
Russian Federation				
Lovozero and others [8]	Peralkaline intrusions/carbonatites	REE, Nb, Ta, others	Unknown	Unknown
South Africa				
Steenkampskraal [12]	Dyke in charnockite	REE, Th	10 282 (measured and indicated)	1.88
Turkey				
Kizilcaören/Eskisehir [3]	Vein	F, Ba, Th	380 000	0.2
USA				
Lemhi Pass [49]	Vein	REE, Th	160 000	~0.4
Wet Mountains [26]	Vein	REE, Th	179 000	0.46
Iron Hill [50]	Carbonatite	REE, Th	24 800	0.003–0.004

2.4. SECONDARY (PLACER) DEPOSITS OF THORIUM AND ASSOCIATED HEAVY METALS

In the Archaean (>3.5 Ga), resistant sand-sized (~0.5 mm) grains of hard, high specific gravity minerals were deposited, along with sand, silt and clay, in coastal, stream and river environments, forming local economic concentrations of HMS (Heavy Mineral Sands). Monazite is one of the highest density minerals and is resistant to both chemical and physical weathering and is thus able to survive transport from distant bedrock sources to its deposition in a stream, river, or coastal plain environment [16]. Monazite is the dominant REE- and Th-bearing mineral in HMS.

Depending on the depositional environment, both modern and ancient HMS deposits may be subdivided into:

- Shoreline placers;
- Offshore placers;
- River placers.

2.4.1. Fossil placer deposits in Precambrian shields

Placers in old Archaean river systems are represented by the gold, uranium and REE-bearing quartz pebble conglomerates of the Witwatersrand (South Africa) and Blind River–Elliot Lake Basins (Canada). Whereas thorium is unlikely to be present in any recoverable amounts in the tailings of the mines exploiting the Witwatersrand Basin, the concentrations of thorium in the pre-Witwatersrand Dominion Reef Group and the Canadian palaeo-placers are significant. Palaeo-placers of undetermined character that contain radioactive minerals have been identified in the Neoproterozoic Nama Basin (South Africa), close to the South Africa, Namibia and Botswana borders. No further data are available.

2.4.2. Placer deposits in modern coastal belts and deltas

Coastal deposits of HMS are the chief source of titanium dioxide for the pigments industry through the recovery and processing of ilmenite, leucoxene (an alteration product of ilmenite), and rutile. HMS are the chief source of zircon, which is often recovered as a co-product. Other co-products can include sillimanite, kyanite, staurolite, garnet and monazite. Some data on the better known and exploited individual deposits are listed in Table 2.

TABLE 2. EXAMPLES OF THORIUM AS BY-PRODUCT IN PLACER DEPOSITS

Country	HMS (Mt)	Monazite (Mt)	Thorium (1000 t)	Average Th content in monazite (%) in monazite
INDIA [54]	948–1064	10.7	838–846	7–8
Kerala	149	1.51	119	
Tamil Nadu	213	2.16	171	
Andra Pradesh	383	3.74	296	
Odisha	181	1.85	146	
AUSTRALIA [42]	>600	6.2	372	6
Murray Basin			281.9	
SW coastal			80.1	
East coastal			13.2	
Eucla Basin			2.3	
SOUTH AFRICA [16]	900		180	5–5.5
Richards Bay			14.900	
Namakwa Sands			9.3	
Dominion Reef			49.3	
Karoo			25.7	
USA [26]		1.51	67	~5
Florida, beach placers		0.43	17	4–4.4
North and South Carolina, stream placers		0.66	33.5	5
Idaho, stream placers		0.42	16.3	1.9–5.5

In India, where ~65% of the shoreline (5800 km) has not been surveyed [54], placers occur along the south-west and south-east coasts. The placers originate from weathered granites, khondalites and charnockites and are composed of quartz sand and heavy minerals such as ilmenite, rutile, sillimanite, garnet, zircon, monazite and others. Monazite accounts for ~1% of HMS resources and occurs in 104 placer deposits, 81 coastal/dune sands, 20 inland sands and 3 riverine placers. Inland dunes are developed as ‘red sands’, rich in iron hydroxide (which imparts the red colour) and which are predominantly ilmenite [54, 55].

In Sri Lanka, the beaches along the regions of north-eastern coast are reported to have the world richest concentrations of HMS [16]. Monazite from south-west region of the island contain up to 12% Th. The sediments are derived from the hinterland, consisting of HFSE-rich charnockitic and garnetiferous gneiss [11].

In South Africa, HMS with monazite occur along both the eastern (Richards Bay, East London) and western coastal strips (Namakwa Sands), derived from sources in the HFSE-rich

Mesoproterozoic Namaqualand–Natal mobile belt [13]. The deposits at Richards Bay are large producers of ilmenite, whereas the Namakwa Sands contain monazite with estimated resources of 9300–10 500 t Th and 4700 t U [56].

In Australia, placer deposits (HMS) occur in Western australia, Queensland, New South Wales, Victoria and South Australia. Current economically extracted minerals include ilmenite, rutile and zircon, accounting for more than 600 Mt in the HMS deposits. The thorium content of the monazite is variable (~6%). Thorium resources in Australia are estimated at 532 000 t, of which 479 000 t are considered recoverable [3]. About 333 000 t Th (inferred resources) are reported for Australian placer deposits. Deposits are clustered in four or five provinces, each characterized by its own geological provenance.

Egypt's Nile delta contains HMS in an area extending over more than 200 km between Rashid (Rosetta) and Dumyat (Damietta). According to old reports, the HMS contain ~50% ilmenite and 0.45–0.6% monazite, which contains 5.1% Th [14]. The uppermost 20 m of the deposits are estimated to contain more than 6 Mt of monazite, representing 380 000 t Th (identified resources 100 000 t Th) [57, 58]. Exploration in Mozambique estimates 7–12 Gt of sands containing 3–5% HMS derived from bedrocks of the Mozambique Belt. Monazite concentrations and tonnages of thorium are not reported. Total resources for Mozambique were estimated at 10 000 t Th [3].

In the USA, strandline beach placer deposits ranging in age from Pliocene to Recent occur in north-eastern Florida and in south-eastern Georgia. The deposits are estimated to host 430 000 t of monazite containing ~17 000 t Th [46]. Additional placers have been found inland..

Deposits of HMS are known to occur along the coastline of Vietnam for more than 1500 km. The largest deposits can be found in the province of Binh Thuan in southern Vietnam. In this region, GPM Asia and Amigo Minerals produce ilmenite, zircon, rutile and monazite.

In Brazil, several monazite-bearing placer districts have been developed intermittently along the central Brazilian coast [14, 16, 59]. Past placer producers of monazite are found along the coast between Campos (Rio de Janeiro) to the south and southernmost part of Rio Grande do Norte to the north. Monazite was recovered as a co-product of the mining of titanium minerals and zircon. Different from most HMS operations, several Brazilian deposits were mined chiefly for their monazite as a source of thorium, with zircon and titanium minerals considered as co-products. Between 1900 and 1947, Brazil exported 56 350 t of monazite concentrate [14]. The only active Brazilian producer of monazite since the early 1990s is the Buena placer district.

China has considerable resources of ilmenite-, zircon- and monazite-rich placer deposits, although scant information has been published on these occurrences. The majority of the HMS resources of China are hosted by Cenozoic deposits formed mainly along the southern and south-eastern coasts [59].

By-product monazite has been recovered from alluvial and coastal HMS deposits in the Democratic Republic of Congo, Indonesia, Republic of Korea, Malaysia and New Zealand. In Malaysia, weathering and decomposition of Sn-rich granites and pegmatites liberate cassiterite together with ilmenite, monazite and xenotime [60]. Downstream, fluvial placers rich in cassiterite can also contain thorium owing to the presence of associated xenotime and monazite. Recently, tailings generated by former tin placer mining have been reprocessed to recover xenotime and monazite, from which 350 t of REOs were produced in 2012 [61]. Recently, monazite has also been recovered from alluvial placers in Thailand [62].

3. THORIUM RESOURCES, MARKET AND PRODUCTION SCENARIOS

3.1. RESOURCE REPORTING, CLASSIFICATION AND UNITED NATIONS FRAMEWORK CLASSIFICATION

Through international efforts coordinated by the United Nations Economic Commission for Europe (UNECE), involving experts provided by Member States, the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC) was established to furnish a generic scheme for classifying and categorizing resources [63]. The first iteration was published in 1947 for coal, and its scope was broadened to include other minerals and solid fuels in 1992, with a subsequent revision appearing in 1997. Since then, the UNFC has been adopted into law in several countries. The scope was broadened further to include oil and gas and uranium in 2004. In the most recent iteration—UNFC-2009—the system was simplified further to allow for multiple commodity application.

Being the sole international system, UNFC-2009 is applicable equally to solid minerals and fluids (e.g. petroleum). UNFC-2009 is currently being broadened to include seamless application to nuclear fuel resources (uranium and thorium), renewable energy systems and injection projects. When operational for these recent additions, UNFC-2009 will be the world's only resource classification system that is applicable to all energy resources.

The UNFC-2009 is intended to harmonize and simplify a variety of tools for resource classification and resource reporting that are currently in use around the world, particularly for commercial scale projects. The UNFC-2009 achieves this by classifying estimations that vary from pre-competitive regional, order of magnitude and scoping studies all the way through to individual projects at different stages and levels of operational and economic readiness. Thus, the UNFC-2009 is usable by both governments and the private sector. The UNFC-2009 classifies resources according to:

- Three primary qualitative criteria: (i) their current level of socioeconomic viability (E); (ii) technical feasibility (F) and (iii) geological confidence or uncertainty (G) (Fig. 3);
- Their quantitative status, which is provable on a 4-point scale, with 1 being the closest to commercial-scale production and 3 or 4 being the furthest away, as measured independently, with regard to the three primary qualitative criteria.

Historically, thorium and uranium deposits around the world have been most commonly reported and classified according to a variety of mineral resource reporting schemes:

- Inter-governmental: The 'Red Book' is a system developed jointly by the OECD Nuclear Energy Agency and the IAEA. It entails a biaxial classification that takes into account the production costs of uranium according to cost band and the degree of geological knowledge. It was intended for reporting international, national, regional and individual estimates of uranium resources, mainly at a governmental level rather than a commercial level. The Red Book classification scheme has also been used to classify thorium resources. The Bridging Document on Nuclear Fuel Resources [64] furnishes, in the context of how a resource specific reporting tool can also be adapted within UNFC-2009, specifications for reporting thorium and uranium resources and for transferring of results between the NEA–IAEA schemes and the UNFC-2009;
- National: Some countries, such as Australia, Canada, China, Ukraine and the USA, have developed their own systems for classification of mineral resources, including thorium and uranium;

- Commercial: The Committee for Mineral Reserves International Reporting Standards (CRIRSCO) system [65], developed and maintained by the CRIRSCO Template, is recognized internationally and used widely to classify in situ commodity resources of all types of mineral deposit. For thorium and uranium deposits, Reports of Exploration Results, Mineral Resources and Mineral Reserves prepared in accordance with the CRIRSCO family of aligned standards and codes, can be reported in the same way following the UNFC-2009 Numerical Codes. Guidelines for mapping data across from CRIRSCO to UNFC-2009 are described in the ‘Bridging Document’ between UNFC-2009 and the CRIRSCO Template, given as Annex III of UNFC-2009 (issued 2013).

Traditionally, the NEA–IAEA classification system reported thorium resources in the same way as uranium resources are reported. However, as thorium has no major market, even though it is or could be produced with other commercially marketable commodities (e.g. REE), thorium can thus be reported by following the UNFC-2009 classification system.

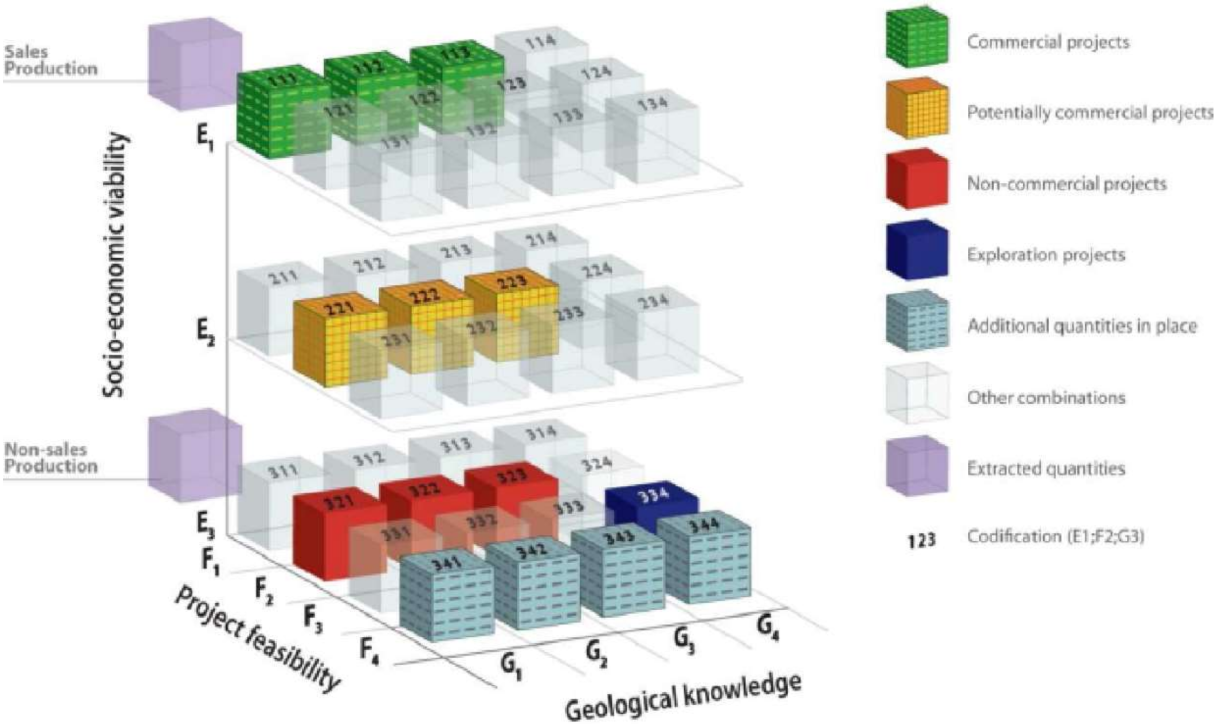

FIG. 3. UNFC-2009 categories and examples of classes (reproduced by permission of UNECE) [63].

3.2. SUMMARY OF WORLD THORIUM RESOURCES

In Section 2, geological types of thorium deposit are described to some detail. A simplified classification of thorium deposits allows them to be grouped into several major types:

- Carbonatite;
- Alkaline/peralkaline rocks;
- Vein-type;
- Metamorphic type;
- Placers.

In Table 3, these types are summarized in decreasing order of importance.

TABLE 3. RESOURCES OF MAJOR THORIUM DEPOSIT TYPES [2]

Type of deposit	Thorium resources (1000 t)	Global thorium resources (% rounded)
Placer	2182	35
Carbonatite	1783	29
Vein-/dyke-type	1528	25
Alkaline rocks	584	9
Other/unknown	135	2
Total	6212	100

As shown in Table 3, global thorium resources were estimated in 2013 at 6.2 Mt. Many uncertainties exist for several countries. Resources for China of more than 100 000 t Th are not verified and may be much higher. In 1984, the total was estimated at 380 000 t Th and much higher resources have been mentioned in a non-official statement at the THEO conference at CERN on 23 October 2013. Thus, the world total may exceed 7 Mt Th.

The world total Th resources, reported in the 2015 edition of the Red Book [2] (table 4), ranges from 6 730 000 tTh to 7 590 800 tTh.

The ages of placer-type deposits vary from Archaean (e.g. the palaeo-quartz-pebble conglomerates in the Witwatersrand Basin of South Africa) to Tertiary. Recent-aged HMS deposits (black sands) exist chiefly in coastal areas in Australia, Brazil, India, Mozambique, South Africa and the USA, as well as in several other countries. Total resources of thorium in placer-type deposits are estimated worldwide to be ~2.2 Mt.

Carbonatite-hosted deposits are distributed worldwide. Typically, the deposits are enriched in REE and/or Nb/Ta. Most of the more than 400 individual deposits may host thorium mineralization. Well documented examples occur in the Australia, Brazil, Canada, Finland, Norway, the Russian Federation, South Africa, Sweden and the USA.

The deposit of Bayan Obo in China has features of a carbonatite and registers an imprint of hydrothermal mineralization, which is the reason for classifying this deposit as polygenic.

Vein-type deposits, including dykes, often exhibit a genetic relationship to magmatic intrusions (granites, alkaline rocks, carbonatites). Examples include the Nolans Bore deposit in Australia, Kizilcaön/Eskisehir in Turkey and the dyke at Steenkampskraal in South Africa.

Alkaline and peralkaline rock types containing thorium resources are typified by contents of alkali elements (Na and K) higher than the content of Al ($Na_2O+K_2O>Al_2O_3$). Examples are mainly polymetallic, such as the Thor Lake deposit in Canada and the Kvanefjeld deposit in Greenland.

TABLE 4. TOTAL THORIUM RESOURCES IN SITU (t)

Region	Country	Total thorium resources (t)
Europe		
	Turkey[a]	374 000
	Norway	87 000
	Greenland (Denmark)	86 000–93 000
	Finland[a]	60 000
	Russian Federation	55 000
	Sweden	50 000
	France	1000
	Total	720 000
Americas		
	Brazil	632 000
	USA[b]	598 000
	Venezuela[a]	300 000
	Canada	172 000
	Peru	20 000
	Uruguay[a]	3000
	Argentina	1300
	Total	1 723 300
Africa		
	Egypt[a]	380 000
	South Africa	148 000
	Morocco[a]	30 000
	Nigeria[a]	29 000
	Madagascar[a]	22 000
	Angola[a]	10 000
	Mozambique	10 000
	Malawi[a]	9000
	Kenya[a]	8000
	Dem. Rep. Congo[a]	2500
	Others[a]	1000
	Total	649 500
Asia		
	CIS[c] (excl. Russian Federation)	1 500 000
	includes Kazakhstan (estimated)	(>50 000)
	includes Russian Federation (Asian part) (estimated)	(>100 000)
	Uzbekistan (estimated)	(5000–10 000)
	India	846 500
	China (estimated)	>100 000 (incl. 9000[a] Taiwan, China)
	Iran, Islamic Republic of[a]	30 000
	Malaysia	18 000
	Thailand[a] (estimated)	10 000
	Vietnam[a] (estimated)	5000–10 000
	Korea, Republic of[a]	6000
	Sri Lanka[a] (estimated)	4000
	Total	>2 524 500
Australia		595 000
	World total	>6 212 300

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[a] Data not updated.

[b] The basis for the estimate of identified (reasonably assured resources + inferred) thorium resources in the USA is a recent thorough review of data published by the US Geological Survey [46,48]. The Red Book indicated earlier estimates of thorium resources in the USA of as much as 770 000 t, which are likely inclusive estimates of undiscovered (prognosticated and speculative) resources. This higher value, which cannot be substantiated, is not given here.

[c] CIS: Commonwealth of Independent States.

3.3. MARKETS

3.3.1. Market considerations for thorium as a by-product

A market for thorium has not yet developed. In addition, a uniform classification of resources and costs of recovery is not available. Once the UNFC-2009 classification is applied by all reporting nations, a better understanding will be generated. A number of countries are already using the UNFC-2009 classification for Th resources. However, a worldwide overview is not yet available.

It has been common practice in base metal production to use terms such as co-product and by-product. These mines often produce several metals such as gold, copper, silver, zinc, lead, mercury, antimony, etc. By-production is employed for resources where the primary product also contains a secondary and even tertiary product. Often, the secondary product is not in itself economic, but its extraction can be facilitated by the primary commodity production process. Co-production is where more than one metal is present in economic concentrations. This is common in base metal ores where, typically, copper and nickel or zinc, lead and silver are produced from a single ore source [65].

Thorium production occurs mainly from REE, usually considered as one commodity which could contribute more than 80% of revenue. Thorium, a commodity of low economic value at present, would then be called a by-product. If there are multiple commodities recovered such as pure fractions of individual REE, other base metals, etc., then all the commodities including thorium will be termed co-products.

3.3.2. Commodity and metal prices

Little information is available for global thorium markets but in general, prices of all metal-based commodities peaked in 2007–2008, but subsequently crashed with the economic downturn in 2008. Prices recovered for certain metal-based commodities by 2011, before sliding down progressively from early 2011 to the present-day. As shown in Fig. 4, metal-based commodity prices are currently (2019) at a 14-year low. Consequently, the mineral industry is under stress and it is generally believed that the low commodity prices will be sustained for the long term. Some of the commodities that are heavily impacted include oil and gas, copper, iron ore, gold, REE and uranium. Most of the metal prices are at 10-year lows (Fig. 4).

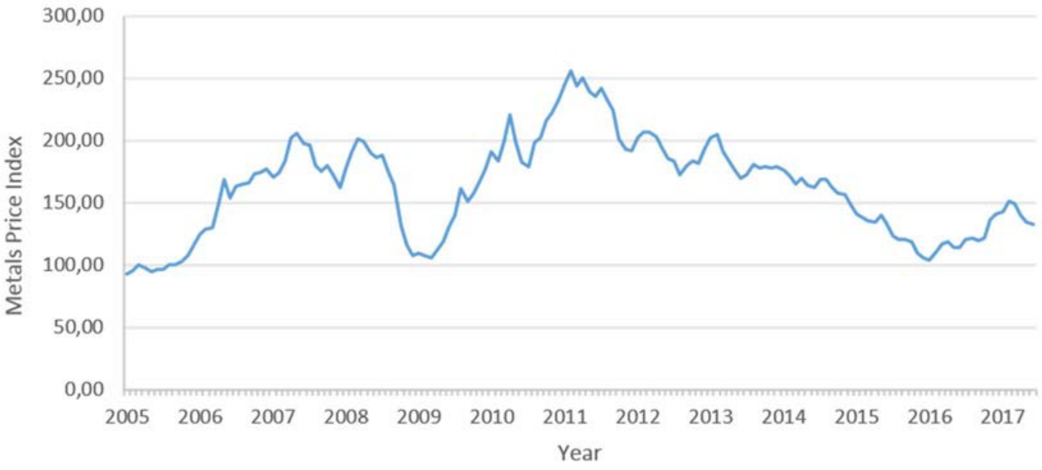

FIG. 4. Commodity metals price index. Includes copper, aluminium, iron ore, tin, nickel, zinc, lead and uranium price indices. (2005 = 77) [66].

3.3.3. Impact on mineral production

A decline has been observed in the quality of new mineral discoveries made in recent years. There are only a few high-grade mineral deposits that can be moved into production. However, focusing only on a few high-quality discoveries will necessitate overcoming many technical challenges and may prove to be too risky for investment.

3.3.4. Productivity and efficiency

A major trend highlighted by the industry itself is that the mining boom since about 2004 has affected it. Productivity, both in terms of labour and capital, has consistently declined. Cost of production has grown, despite lower inputs costs such as fuel and energy. Anecdotally one of the major reasons for the decline of productivity is the growing integration gap seen in the mining life cycle. For example, mine blasting and excavation may not be synchronized with crushing and grinding activity and could produce ore in sizes not suitable for the designed crushing circuit, or may under- or over-deliver, resulting in sub-optimal capacity utilization. Mine remediation in a progressive manner will help in drastically cutting down the costs, but this is often neglected in many operations.

Decline in productivity is often addressed by companies by cost cutting, such as decreasing production and laying off employees, which often brings in modest and short-term results. In many cases, selective processing of high-grade material is resorted to, which builds up a stockpile of low grade material that will have to be addressed at some point in the future, and there is no guarantee that market conditions will be favourable.

During periods of relative market improvement, mineral industries have not always capitalized on the favourable market conditions existing for previous years. As highlighted by the relative lack of requests for Thorium-related activities from the IAEA, at appears that there is little sustained interest from Member States in innovation or in training of human resources to make production operations more efficient. For example, mining and processing losses remain significantly high in many operations compared to the industry average, relative to efficiencies in other mineral commodities.

3.3.5. Socioeconomic impacts

With little specific information regarding global thorium markets, some insights may be gained from general metal markets. In recent years, write downs and impairments in mining assets have been observed. One report estimates that the top 40 mining companies in the world suffered a combined loss in excess of US$156 billion in 2014 [67]. There is a declining availability of funds for exploration, especially for the 'junior' companies which are responsible for a large proportion of greenfield exploration. A few mining projects are put under care and maintenance until the markets recover. A number of advanced projects planned for immediate start have been put on hold. Large layoffs of human resources have become the norm.

There has been a broad trend in reduction in payment, taxes and royalties from the mineral sector. This has impacted growth in many countries, especially for local governments. Economies are contracting, and millennium development goals are not being met. Social licence to operate has become critical as dissatisfaction in local communities leading to conflicts, sometimes violent, has been seen in all regions.

There are instances where Thorium is seen as being problematic rather than a resource of value, with many countries such as Malaysia and Thailand reconsidering Thorium extraction. This approach has This approach has resulted in under reporting or exclusion of thorium values. Often the issue of thorium in the tailings creates a social licence issue when the project approaches start-up, increasing business risk.

3.3.6. Rare earth markets

As a significant proportion of thorium resources are by- or coproducts of REE deposits, there is a strong link to economic issues of Th to REE. Since the beginning of the millennium China has become the most important source of REE production, supplying almost 97% of world requirements. In order to ensure that the mining and processing activities were more sustainable, in 2010 the country decided to reduce production drastically and reduce exports by 30%. This led to volatility in the markets and REE prices increased significantly, along with the share prices of companies elsewhere. This prompted increased interest in exploring for REE prospects that could be quickly brought into production and thereby meet the supply deficit [68].

The REE industry outside China has started declining, which can be seen in the example of the Rare Earth/Strategic Metals Exchange Traded F (REMX), which was launched in 2010 and which lost 74% of its value in the following five years. Another significant event was the filing for bankruptcy of the USA-based rare earths mining company Molycorp in June 2015 and by the Canada-based Great Western Co., which sold the Steenkampskraal mine to Steenkampskraal Thorium 100.

In parallel, REE applications looked to find other, cheaper substitutes, which in many cases was not successful. However, users have also found different ways to reduce demand. Therefore, although the demand for REE will continue and the market is expected to be dominated by supply from China, there is now increased processing capacity in other countries, especially in France, India and Malaysia.

3.3.7. Rare metals market

The geological relationships between thorium and REE warrant a discussion with markets related to the latter. Niobium is sometimes grouped together with tantalum, and these are important additives in high strength low alloy steel, which is widely used in the oil and gas industry, as well as in the construction and transportation sectors. Stainless steels and super alloys also use significant quantities of niobium. Tantalum is required for the manufacture of electronic components.

Niobium and tantalum are elements that usually occur together in minerals such as pyrochlore. Host rocks for Nb- and Ta-bearing minerals are mainly alkaline complexes and carbonatites. Association with REE is often observed. Examples of Nb–Ta–REE mineralization is the Mt Weld carbonatite in Australia and Araxa in Brazil. Another example where REE, Nb and Ta are concentrated is in the giant deposit of Bayan Obo in China. Unlike Nb-bearing mineralization, Ta-mineralization tends to be enriched in specific granites and pegmatites, as evidenced by worldwide occurrences.

Niobium resources are essentially identified in Brazil, with smaller resources reported from Canada, China (Bayan Obo) and the USA. Advanced exploration projects are ongoing in many other countries (Table 5 [69]).

TABLE 5. WORLD NIOBIUM RESOURCES [69]

Country	Proved and probable reserves (t of ore)	Nb_2O_5 (t of Nb oxyde)	Inferred resources (t of ore)	Nb_2O_5 (t of Nb oxyde)
Brazil	452 200 000	11 142 740	11 900 000	214 200[a]
Canada	32 086 000	179 682	37 912 000	219 889
USA	150 000[b]		n.a.	n.a.
Total	484 436 000	11 322 740	n.a.	n.a.

[a] Only includes resources from Catalão (Anglo-American (2011)).

[b] Uneconomic at 2010 prices (Papp United States Geological Survey personal communication 2011).

Resources: a mineral resource is a concentration of minerals or a body of rock that is, or may becomr, of potential economic interest for the extraction of a mineral commodity.

Reserves: a mineral reserve is the part of the resource which has been fully grologically evaluated and is commercially and legally minable using current technology. [69]

Niobium production is dominated by Brazil (45 000 t Nb in both 2012 and 2013), where the Araxa deposit comprises the major source of supply. The Nb-bearing mineral is barrio-pyrochlore, which constitutes ~4.5% of the ore. Currently, the weathered top of the deposit is considered to be the most economically attractive. About 5% monazite is also present in the ore, which could be a source of both thorium and REE. Currently, the monazite is not extracted.

Tantalum frequently occurs in the mineral columbite, a mixture of niobite and tantalite, also known as coltan. Tantalum resources (Table 6 [70]) are located mainly in Brazil, but significant resources also occur in Australia, Burundi, Canada, China, Democratic Republic of Congo, Nigeria, Rwanda and elsewhere.

TABLE 6. WORLD TANTALUM RESOURCES [69]

Source	Estimated resources (t Ta_2O_5)	Proportion of resources (%)	Reserves (t Ta)
Brazil	129 274	40	87 360
Australia	65 771	21	40 560
China and South-east Asia	33 112	10	7 800
Russian Federation and Middle East	31 298	10	-
Central Africa	28 576	9	3120
Other, Africa	21 318	7	12 480
North America	5443	2	1500
Europe	2268	1	-
Total	317 060	100	152 820

The major tantalum supply currently comes from Rwanda and the Democratic Republic of the Congo, where some of the projects are under close audit with respect to the 'conflict minerals' regimes of the EU and the USA. The trend for niobium consumption is expected to continue to closely follow the production Nb steel alloy, and many new projects are being developed to increase the supply (Table 7 [69]).

TABLE 7. UPCOMING Nb–Ta PROJECTS [69]

Deposit	Country	Company	Type	Resources[a] (Mt)	Nb_2O_5 (%)	Ta_2O_5 (%)
Anita	Canada	Les Mineraux Crevier	Carbonatite–nepheline syenite	23.75	0.186	0.019
Motzfeldt	Greenland	Ram Resources	Alkaline–peralkaline granite	500	0.13–0.15	0.011–0.013 0.023
Crevier	Canada	MDN Inc.	Carbonatite–nepheline syenite	25.4	0.2	0.018
Kanyika	Malawi	Globe Metals and Mining	Alkaline–peralkaline granite	21	0.41	0.025 0.014 0.023 0.019
Abu Dabbah	Egypt	Gippsland	Li-Cs-Ta granite	44.5	n.a.	
Nuweibi	Egypt	Gippsland	Li-Cs-Ta granite	98	0.0095	
Marropino	Mozambique	Noventa	Li-Cs-Ta granite	7.4	n.a.	
Upper Fir	Canada	Commerce Resources Corp.	Carbonatite–nepheline syenite	36.4	0.17	

[a] Includes all categories of resource.

3.4. PRODUCTION SCENARIOS

World production of thorium prior to 1988 was reported to be 37 500 t [9]. In the period 2008–2013, monazite production fluctuated between 6620 and 7300 t (Table 8), and the theoretical Th content was ~500 t annually. However, its recovery, except for India, is not reported. World total monazite output in 2013 had a theoretical Th content of around 400 t at an average grade of 6% Th.

Historical and recent production of monazite is known from China, the Democratic Republic of the Congo, Indonesia, Democratic People's Republic of Korea, Republic of Korea, Nigeria, Sri Lanka, Thailand and the former Soviet Union, as well as possibly other countries, too, including Australia and South Africa.

At the time of publication, India is the only country where thorium is produced as a by-product. Currently, recovery of thorium as a by-product of REE production from monazite is the most probable option. Current world production of REE is estimated at around 110 000 t. Global resources of REE may amount to more than 140 Mt. Thorium concentration in the monazite varies depending on the deposit and therefore the quantities of thorium that might be available through separate recovery are unknown.

India is currently the sole country where thorium is extracted from monazite obtained by separation from other heavy minerals in placer deposits. Indian Rare Earth Ltd (IREL) produces thorium from a placer deposit at a plant at Cochin, Kerala. Its thorium production is not disclosed. However, it is assumed that it is sufficient for current use in reactors and for the near future.

TABLE 8. MONAZITE PRODUCTION IN 2013

Country	Production of monazite in t
India	5400
Malaysia	600
Vietnam	369
Brazil	250
Total	6619

As stated, the recovery of thorium from monazite is possible and is the most realistic option in the near term. However, should demand for thorium arise, then other methods of recovery as a by-product may be utilized. In the past, some countries have utilized monazite for the extraction of thorium, mostly as a by-product. For example, in Brazil, monazite from the Buena mine was treated to recover thorium. This operation was terminated in 1960 (see Case Study: Brazil); although, it was restarted in 2011 and the ore stockpiled awaiting processing. Other countries may have extracted thorium, such as France and Germany.

The separation of monazite from heavy minerals concentrate is unpopular in most countries owing to its radioactivity. However, should the demand for thorium increase then the separation and recovery of thorium as by-product arise. In the case of Australia, monazite has been separated for export mostly and used for the production of REE until 1996. Currently, Australia, a former producer of monazite, does not separate monazite from heavy minerals but disposes of monazite, together with other waste, back into the sea.

In South Africa, a feasibility study by Great Western was conducted on the currently dormant Steenkampskraal mine in the Western Cape. Lately, the deposit was acquired by Steenkampskraal Thorium 100 for the planned co-production of Th and REE once the reactor tests in Norway by Thor Energy have been successfully completed (see Case Studies: South Africa).

At present, the Canadian Pele Mountain Company is considering using tailings from previous uranium extraction from quartz pebble conglomerates in the Elliot Lake District, Ontario, Canada. The tailings contain REE and thorium, affording the company an economic option. In parallel, treatment of imported monazite is being considered by the company (see Case Studies: Canada).

To provide an indication of future availability of thorium, a list of current and potential thorium producers is given in Table 9.

TABLE 9. PRESENT AND FUTURE POTENTIAL THORIUM PRODUCERS

Country	Present or potential producer	Deposit type	Thorium resources (t)
India	IREL	Placer	838 000–846 000 by-product
Australia	Potential, Various	Placer	333 000–372 000 by-product
Canada	Potential, Pele Mountain, Potential, Avalon Rare Metals Inc.	Tailings of QPC REE	100 000 by-product 1200 by-product
Brazil	Industrias Nucleares do Brazil	Placer	
South Africa	Various Great Western	Placer Dyke	180 000 by-product 11 700 co-product
USA	Various	Placer	67,000, by-product
Total of 6 countries		Mainly placer, by-product, one co-product	2 376 900–2 415 900

4. EXPLORATION AND EVALUATION OF THORIUM RESOURCES

4.1. HEAVY MINERAL SANDS

4.1.1. General

Exploration for HMS deposits is usually easier than exploration for Th and REE deposits in hard rocks or for other commodities, such as metallic or energy minerals. At the beginning, in the exploration reconnaissance stage, a detailed study of the geological environment, using for instance remote sensing, is essential. In the case of placer deposits, their occurrence is linked to either coastal environments or river/stream systems.

Many HMS deposits are indicated by their surface expression, by the visible presence of minerals (black sands). Once the region of interest is positively indicated, detailed investigation is necessary, and the method employed depends on the specific type of occurrence/deposit (surficial, covered by overburden, etc.). In general, areas of interest are evaluated by drilling (auger drilling) at various intervals, trenching, bulldozer excavation and others, depending on the character of the deposit. Sampling of drill material, trenches, etc., is undertaken initially with on-the-spot visual screening, followed by a detailed laboratory investigation which includes microscopy and physical and chemical analysis. Mineral separation is essential for the identification of components of the HMS. This is undertaken in various steps.

A detailed description of exploration for other types of thorium mineralization associated with REE, such as those hosted in carbonatites, vein-type deposits, etc., is given in [37].

At present, placer deposits occurring along coasts are very important types of heavy mineral assemblage and those countries having promising environments will employ the requisite exploration methods. Mineral separation exploits variations in the mineral assemblage which may vary from deposit to deposit. For countries interested in the mining of coastal placers and utilization of monazite, the Indian experience in exploration has been chosen as an example.

4.1.2. Indian context

In India, monazite occurs in beach placers together with other heavy minerals, namely ilmenite, rutile, leucoxene, garnet, zircon and sillimanite. Beach sand mineral (BSM) or HMS exploration in India date back over a century; the earliest recorded activity commencing with discovery of monazite in 1903 along the Travancore coast in southern India. Historically, owing to the radioactivity of the monazite, exploration is carried out under the control of Government by the Atomic Minerals Directorate for Exploration & Research, a unit of the Department of Atomic Energy. IREL, a wholly owned State company, is the only entity permitted to recover and process monazite.

4.1.2.1. Nature of occurrence

India has a coastline of over 7000 km which includes varied geomorphological features such as bays, creeks, promontories, headlands, narrow beaches, broad deltas, lagoons close to coastal plains, mud flats, mangroves, inland red sediments, etc. The width of the beaches varies from 100 m to more than 1 km. The western coast of India has narrow beaches whereas those on the eastern coast are much wider. Remote sensing studies have revealed many palaeo-strand lines, particularly along the east coast, thereby enhancing the possibility of locating buried heavy mineral deposits. All the major deposits are distributed in four states: Odisha, Andhra Pradesh, Tamil Nadu and Kerala. The mineralized horizon occurs as horizontal layers extending for kilometres both along and across the coast. For operational convenience, the extent of deposits is usually marked by geomorphic features, e.g. river mouth. Various factors such as wave energy, coastal configuration, direction of wave front and, above all, the hinterland rock composition control the heavy mineral concentration.

5.1.2.2. Optimum sample spacing

For assessing BSM resources, different sample spacings are adopted. Hand augers and Conrad bunks are usually deployed to collect the samples. Sample spacing is also influenced by coastal geomorphology, habitation, industry requirements at a particular time and variations in total heavy mineral (THM) content across the deposit. The drilling and sampling grid, therefore, may vary from area to area, i.e. 3000 m × 500 m, 2000 m × 200 m, 1000 m × 500 m, 800 m × 200 m, 200 m × 200 m, 200 m × 50 m, 100 m × 50 m, 60 m × 30 m, 30 m × 30 m. Geostatistical techniques are also used to determine optimum sample spacing parameters.

4.1.2.3. Estimation of resources

Borehole samples are collected at every 1.50 m depth and a representative portion of the sample is taken for further analysis. Resource estimation is based on grouping of composite samples and generally values of >2% THM are considered for resource estimation. However, in a few barren areas, resources are also estimated for grades less than 2% THM. At present, nearly 50% of coastal length has been explored and a resource of 1065 Mt of THM has been estimated, which includes 11.93 Mt of monazite. The ThO_2 content in the monazite varies in the range 7–10%.

4.1.2.4. Conservation of resources (from sea erosion, human encroachment, etc.)

The heavy mineral resources are exploited within the provisions stipulated under Coastal Regulatory Zone notifications.

4.1.2.5. UNFC-2009 classification

The Indian Bureau of Mines, part of the Ministry of Mines, maintains the National Inventory of Minerals (www.ibm.nic.in). Recently, the UNFC-2009 classification became widely accepted, although adapted to Indian requirements. To do so, all the mineral deposits, irrespective of the mineral, are classified into seven categories, primarily based on the deposit configuration. It is found that, contrary to their dimensions and continuity, the BSM deposits are grouped under the category 6, i.e. Placer and Residual Mineral Deposits of Hill and Valley Wash. However, the BSM deposits in India have distinct characteristics (Table 10) compared with the Residual Hill and Valley Wash deposits.

TABLE 10. CHARACTERISTICS OF BEACH AND INLAND PLACERS IN INDIA

Parameter	Beach and inland placers
Extent	Aerially extensive, thicker deposition
Grain size	Medium to fine
Nature	Constantly reworked and upgraded
Shape and grade	Uniform over long distances, homogenous
Resources	Large (millions of tonnes)
Mineralogy	Monazite, zircon, ilmenite, rutile, garnet, sillimanite, kyanite
Variability in grade and thickness	Uniform, minor variations

4.2. MONAZITE IN CHARNOCKITE DYKES

Charnockite dykes are found mainly in South Africa. However, exploration methods described in relevant publications [12, 13, 43, 44] may be applicable in other countries having similar geological environments. In general, prospecting requires specific geological knowledge:

- Geological age (Palaeozoic or older);
- Metamorphism at temperatures above 700ºC resulting in granulites and charnockites;
- Presence of mafic intrusives (gabbro–diorite) as possible results of differentiation.

In the case where the presence of monazite and/or other radioactive minerals is indicated in the target region or in nearby placers, radiometric and/or magnetic methods may be implemented. Supporting studies on structural geology, geochemistry and economic geology may also be applied.

Exploration of thorium deposits, other than the above-mentioned placers, is, depending on the type of deposit, generally directed at exploration for uranium-bearing minerals or for rare metals.

5. FEASIBILITY STUDIES ON MINING AND PROCESSING

5.1. GENERAL

As noted previously, thorium tends to occur with uranium in monazite, vein associated minerals or in association with niobium and tantalum in specific magmatic rocks. In the sedimentary cycle, monazite can accumulate in ancient and recent beaches or in river beds. Other concentrations are found in laterite, phosphate, coal and lignite.

A comprehensive evaluation of the social, economic and physical environment implications of exploitation are required, including:

- A historical background of the prospected project;
- A description of the main product, by-products and co-products, accounting statements, details of operations, management, marketing, policies, financial data, legal requirements, tax obligations, analysis of competitors and other companies;
- Available technologies, engineering capabilities, are parts of any feasibility process, leading to a positive decision, the capital and operational costs required and expected revenues.

Depending on the thorium association, feasibility studies may vary in nature and depth but are conducted by a group of experts to analyse the strengths and weaknesses of the project and ultimately advance the project through the various stages to full-scale operation, depending on the determination that the project is both technically and economically feasible. The pertinent type of information required to evaluate a placer project are presented below.

5.2. FACTORS TO CONSIDER IN A FEASIBILITY STUDY

To assess the viability of a potential thorium project, a considerable amount of information is required including details of the geology, mineralization, local setting, mining and mineral processing methods, management of wastes, regulatory requirements, community considerations and overall project economics.

The technical considerations will vary greatly according to the project. Regulatory considerations will vary based on national and local regulatory requirements. A crucial consideration nowadays is the need to understand the concerns and sensitivities of local communities and to establish and maintain dialogue with them.

Table 11 provides a list of factors that need to be taken into consideration when evaluating the viability of a project. However, the list in Table 11 is provided only as a starting point, as project and site-specific considerations will determine the focus and scope of any project evaluation.

TABLE 11. LISTING OF IMPORTANT CONSIDERATIONS IN EVALUATING THE VIABILITY OF A POTENTIAL PROJECT

Item no.	Description
1	Summary
2	Introduction
3	Property description and location
3.1	Licences of occupation
3.2	Royalties and other encumbrances
3.3	Permits
3.4	Environmental liabilities
4	Accessibility, climate, local resources, infrastructure and physiography
5	Property history
5.1	Discovery
5.2	Historic exploration
5.3	Historic mining and processing methods
6	Geological setting and mineralization
6.1	Regional geology
6.2	Local geology
6.3	Property geology
7	Mineralization
7.1	Historical mineralogical studies
7.2	Mineralogical studies on the mine property
7.3	Detailed description of mineralized zones
7.4	Discussion of mineralized zones
8	Exploration
9	Drilling
9.1	Historic holes
9.2	Property drilling programmes
9.3	Data collection and verification
10	Adjacent properties
11	Mineral processing and metallurgical testing
11.1	Conceptual process design
11.2	Primary mineral(s) (e.g. uranium-, niobium-bearing)
11.3	REE
11.4	Thorium
12	Waste management
12.1	Waste rock
12.2	Mine water
12.3	Tailings management
13	Mineral resource and reserve estimate
13.1	Mineral resource
13.2	Mineral reserve
14	Mining methods
14.1	Alternative mining methods considered
14.2	Selected mining method(s)
14.3	Mine development for preferred method
15	Mineral processing and metallurgy
15.1	Results from past production and previous testing
15.2	Mineralogy
15.3	Test programme
15.4	Flotation tests
15.5	Leach tests
15.6	Selected recovery method

Item no.	Description
16	Project infrastructure/transportation
16.1	Access roads
16.2	Electricity
16.3	Natural gas or propane
16.4	Other
17	Market studies and contracts
17.1	Primary mineral (e.g. uranium-, niobium-bearing)
17.2	Rare earths
17.3	Thorium
18	Environmental studies, permitting and social or community impact
18.1	Introduction
18.2	Permits, licences and other legislative requirements
18.3	Environmental baseline studies
18.4	Environmental assessment
18.5	Decommissioning and closure planning
18.6	Environmental risk assessments
18.7	Radiological assessments
18.8	Environmental management strategies
18.9	Occupational health and safety
18.10	Socioeconomic and social considerations
18.11	Community relations
19	Capital and operating costs
19.1	Capital costs (CAPEX)
19.2	Operating costs (OPEX)
20	Economic analysis
21	Other relevant data and information
22	Interpretation and conclusions
23	Recommendations
24	References

5.3. EVALUATION OF A PLACER DEPOSIT

5.3.1. Minimum size and production activity

Monazite mining started around 1870 in Brazil, and later in India and other places, and lasted up to about 1930. Mining was aimed at producing thorium nitrate for the gas mantle industry. Radium-228 was a by-product of thorium nitrate residues and was used for medical-based radium therapy. When the gas mantle market disappeared, monazite lost market as a commodity, regaining it for REE production between about 1950 to 1965. From 1965 onwards, the Mountain Pass era dominated up to 1984, at which point China started to dominate the REE market up to 2009–2010. Australian monazite was processed at the former Rhône-Poulenc La Rochelle, France, plant until 1984–1985. After the Chinese decision on REE tightening the export quota in 2010, monazite may become a potential source for REE, provided its problematic Th content can be resolved. If ^{232}Th is to be used as nuclear fuel in commercial power plants, its storage as unwanted ‘waste’ after REE extraction from monazite is no longer required.

HMS deposits are mined for their ilmenite, rutile, leucoxene and zircon content and have the potential to yield significant resources of REE contained in the monazite component. HMS may also contain minor xenotime with traces of uranium and thorium. The monazite portion of the HMS was sent to specialized metallurgical plants to extract the containing REE. The corresponding thorium compounds were stored or sent back to the mine site up to a permissible radiation level (40–600 Bq/kg). As always, a 'minimum size' plant or mine for commercial thorium depends on and is regulated by the REE production capacity [70].

5.3.1.1. Mining

If thorium is to be obtained from sources other than HMS then mining operations will be conducted for the prime economic target (e.g. rare metals) and the ore might be readily available for thorium recovery through further processing. For HMS, the two mining methods used, depending on the physical, social and economic features of the deposit, are:

(a) Dry method:

First, the overburden is removed with earthmoving equipment (scrapers, bulldozers) and stockpiled. The ore is then extracted and hauled to a stockpile and then transferred to a wet plant for mineral processing operations and separation. The tailings are pumped back to the mine site for backfilling.

(b) Wet method:

In principle, two wet mining methods are applied: dredging and hydraulic mining.

- Dredging: A powered suction dredge floats within a pond and sucks material from the bottom of the pond, mixed with water. The slurry is sent to a wet mill where spiral concentrators separate and concentrate the heavy minerals. Electromagnetic separators may be also used. The dredge advances across the pond while the processed sand tailings are spread behind for revegetation at a later phase;
- Hydraulic mining: The sand material is washed down by applying a strong water jet and the slurry pumped to the wet concentrator where the heavy minerals are separated from the waste.

5.3.1.2. Processing of ores

(a) Physical mineral processing:

Spirals are used in both mining methods at mine sites to separate large quantities of quartz sand from the heavy minerals. The sand pulp is sent to the spiral chute and controlled water added to adjust pulp density, moving down under the influence of hydraulic drag forces and centrifugal force separating the heavy minerals from waste sands. The concentrate flows into a hopper and is then collected through a pipeline. The tailings are discharged to a sand pond.

As in any mineral processing flowsheet, the effect of a combination of available unit operations — mainly gravimetric, electromagnetic and electrostatic — will depend upon the particular fractions bearing the desired elements of the treated heavy sand. In the spirals, the particles sort themselves according to size, shape and density, where the lighter, coarser and more equant particles are carried by water to the outside of the trough. Heavier, finer and flatter particles are separated by remaining on the inside of the spiral.

The heavy mineral concentrate is progressively removed from the trough by splitters located along the length and at the base of a spiral. The final product from the gravimetric method is a heavy mineral concentrate that is suitable for further mill processing. As a rule, the heavy fraction containing monazite, zircon, ilmenite and rutile is dried and subjected to electrostatic separation which separate the conducting fraction (rutile and ilmenite) from the non-conducting fraction (monazite and zircon). From the electrostatic separators, both the conducting and non-conducting concentrates are then subject to electromagnetic separation, thus separating the magnetic ilmenite from the non-magnetic rutile from the conducting fraction, and the magnetic monazite from the non-magnetic zircon, respectively. Before the advent of modern spiral concentrators, shaking tables were used.

(b) Hydrometallurgy of bastnäsite and monazite/xenotime concentrates:

Figure 5 shows a processing flowsheet for extracting REE from different major REE-bearing minerals. In the earlier days of monazite mining, the main interest was thorium production.

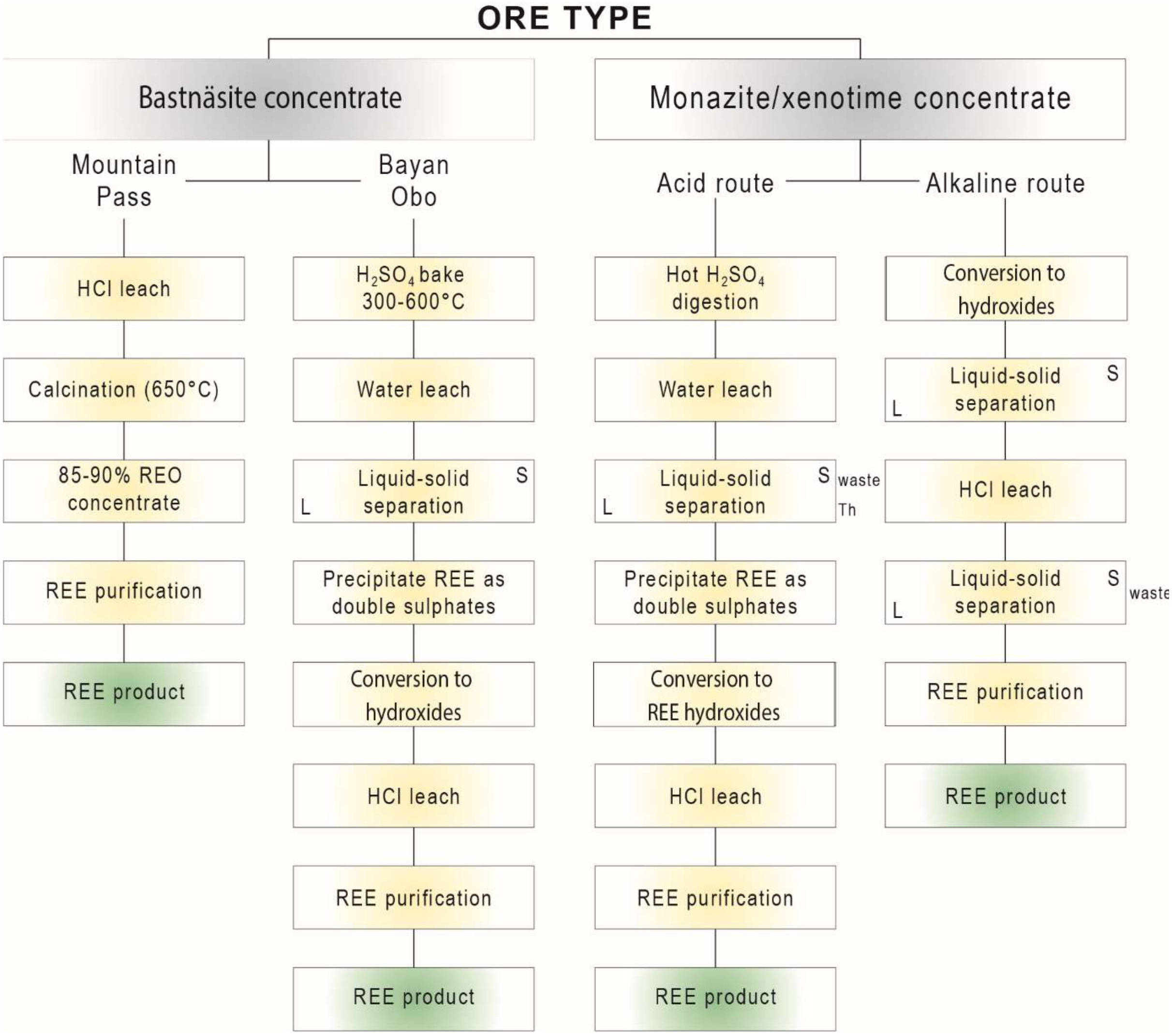

FIG. 5. Processing routes for extracting REE from concentrates (adapted from [71]).

Monazite concentrate is finely ground and heated in double its mass of sulphuric acid, for chemical dissolution. The leach slurry is then cooled, and the elements of interest dissolved in water. The admixture is then allowed to settle. Following this process, selective precipitation is completed whereby thorium is concentrated mainly in the first of the precipitated fractions [72, 73].

If the monazite fraction of the HMS is to be processed for REE recovery and marketing, then a wide range of modern chemical methods of treating the monazite concentrate in order to recover nuclear grade thorium, uranium and rare earths in usable form could potentially have to be utilized, e.g. by solvent extraction techniques and extractants (a technique applied to uranium processing). Several methods are available for leaching monazite with aqueous inorganic acids (HCl, H_2SO_4, HNO_3) followed by solid–liquid separation, which was typically accomplished through either filtering or counter-current decantation. Liquid–liquid separation or solvent extraction via commercially available organic substances (D2EHPA, HEHEHP, TBP, Versatic acid 10, Aliquat 336) is performed in order to purify and concentrate individual rare earths or mixed oxides. Depending on the hydrometallurgical process selected, this purification and concentration process may have required several hundred mixer–settler stages to achieve the required products and separations [74-76].

Originally, solvent extraction methods were developed at the Battelle Memorial Institute, Oak Ridge National Laboratories and Ames Laboratory, by Rhône-Poulenc in France and at R&D institutions in the former Soviet Union and at the Indian Rare Earths Factory at Alwaye. For monazite, the process that was used up to 1990 was the Rhône-Poulenc solvent extraction process, patented by the former Rhône-Poulenc of France (now Solvay).

If thorium is to be recovered, there are several industrial processes for thorium compounds and oxide production described by Soddy since the early 1900s and additional ones developed during the 1940s and 1950s which utilize solvent extraction and/or ion exchange in industrial operations. Obtaining thorium compounds from the monazite concentrate is, in general, easier than that of the rare earth's constituents.

The process consists of acid or alkaline leaching followed by selective separation and precipitation of thorium, via hydrolysis of salts, complexing chemical compounds and exploiting differences in solubility of the several salts thus produced. Purification of the obtained thorium salts is performed by crystallization, solvent extraction and/or ion exchange techniques.

A complete account of the hydrometallurgy of thorium production from monazite concentrates is given in [77]. This includes references to uranium, rare earth and thorium compounds developed by TORTA II and manufactured by ORQUIMA in São Paulo from 1948 onwards. Indian practices both at the Indian Rare Earths Factory at Alwaye and further thorium compounds purification and its conversion to sulphate or nitrate were carried out at the Atomic Energy Establishment factory at Trombay [78].

In France, the Societé des Produits Chimiques des Terres Rares (after 1959 by Saint Gobain and Pechiney, after 1969 by Rhône-Poulenc) worked with, and patented, a process for monazite treatment that was closely followed by both Indian and Brazilian enterprises.

For power reactor purposes, thorium metal, thorium alloys and thorium oxide can be prepared at specific and designed properties [79, 80].

5.3.1.3. Radiation protection

An IAEA review [81] of the experience at rare earth facilities around the world indicates that radiation exposures to workers can be readily managed to fall well within established dose limits. Historical radiation doses to workers associated with monazite processing are provided by Pillai [82], Haridasan [83] reported individual doses arising from the retrieval and processing of thorium hydroxide concentrate for the recovery of uranium and production of thorium oxalate

5.3.2. Environmental management plan

For other environmental aspects, environmental management plans are prepared based on the detailed assessment of the impacts presented in the environmental impact assessment (or similar assessments). The environmental management plan addresses the construction and operational phases of the project, separately addressing the various applicable environmental components, i.e. ambient air quality, ambient noise quality, terrestrial ecology and soil and groundwater quality. The environmental management plan comprises the following elements:

- Organization structure for implementation of the proposed control measures;
- Control measures for mitigating residual environmental impacts;
- Auditing/monitoring arrangements to assess the effectiveness of implementation of the mitigation measures;
- Methods for implementation of any corrective/preventive actions and the review process.

5.3.2.1. Health, safety and environment (environmental impact study, environmental impact plan)

HMS mining is a well-known and established commercial activity, although in the present-day it may raise significant social issues arising from the geographic location and the environmental and social impacts it may have. This includes consideration of other competing socioeconomic activities and/or the presence of radiation, noise and impacts to the environment. In India, under the guidelines framed by the Atomic Energy Regulatory Board, individual processors of beach sand must separate and store the monazite fraction safely.

No individual or entity is permitted to process monazite in any manner without a licence from the Department of Atomic Energy. Furthermore, no licences have been given in India to any private party to process monazite and separate thorium. As thorium is radioactive, occupational health provisions are required for handling materials containing this element.

As regards monazite processing, there is a controlled need to monitor the radioactive doses throughout the processing operations. Historical monitoring has shown that the lighter fraction out of the magnetic separator has a total radioactivity of 170–320 Bq/g and a monazite concentrate (99%) that after alkaline digestion, filtration and neutralization produces a cake (TORTA II) of Th and U hydroxide having a total radioactivity of 1820 Bq/g. Typically, this fraction is stored or processed. If processed, it yields a chloride-based solution of Ra and REE that, after precipitation of REE, produces a REE barren solution with an overall radioactivity of 4360 Bq/g (figures were only reported in Bq/g, not Bq/l).

Codes of practice and safety guides for radioactive waste management in mining and mineral processing in HMS extraction are in place in many countries and regulate the activity in all the major players dealing with mineral sands. Transport of such material is also regulated in some countries that have experience in HMS processing.

5.3.2.2. Storage of thorium product

Thorium compound wastes (naturally occurring radioactive material (NORM) wastes) should not be left without proper care in drums and bottles as it can be highly reactive and oxidize, lids can become loose, and contamination can be spread to the outer surfaces of the bottles or the workspace. Some reported experiences and good practices on the storage of thorium nitrates and hydroxides are available from the THOREX process in the USA, ANDRA in France, and NSSI, also in the USA.

While there is currently no significant market for a thorium product, progress is being made on the development of thorium-based nuclear reactors. If potential sale of the thorium is being considered, then thorium concentrate could be safely and securely stored on-site in containers suitable for future export. Alternatively, engineered containment can be designed and built for both short term and long-term storage. Experience with such storage has been demonstrated at Indian rare earth processing sites, where engineered silos clad with adequate radiation shielding have been used [82]. Alternative techniques have been documented by the IAEA [81] and include Brazilian processors that have stored the thorium product in rubber drums placed in shallow ground silos and shallow (3 m) concrete trenches. In Malaysia, the thorium residue, combined with other residue, has been stored in drums at an approved surface storage facility, although the waste will eventually require permanent disposal (likely using sub-surface engineered cells).

5.3.2.3. Management of by-products and residues

Wastes generated during the processing of monazite represents a potential source of radioactivity as almost all of the thorium and uranium and their respective decay products in the plant feed typically report to the thorium concentrate and final waste residue. A specifically designed waste disposal facility can be used to permanently dispose of the chemical process residue. The amount of solid residue produced will depend to a large extent on process specifics. Although most of the thorium and uranium are anticipated to end up in the thorium products, some level of radioactivity may also end up in the residues. Thus, while the radioactivity content of the residues is expected to be low, testing is recommended prior to final selection of management practice. The process residue has little to no future value and should be disposed as a radioactive waste.

Disposal design criteria that should be considered in developing waste disposal plans for these materials include:

- Land tenure: The land tenure and use should be secure in order to ensure changing land uses so that in the future this does not conflict with the use of the site as a radioactive waste storage area. Buildings should not be permitted on the waste disposal facility,

- Physical stability: The placement of the waste disposal facility must be selected to minimize the potential for containment failure due to physical issues such as wind erosion, floods and earthquakes;

- Prevent migration: The waste disposal facility should permanently inhibit infiltration of surface water (i.e. precipitation, overland flow) and groundwater, thereby reducing the potential for the migration of radionuclides from substandard disposal facilities;

- Radiation exposure: The waste disposal facility should be designed to effectively minimize or eliminate the radiation exposure of workers, members of the public and the environment. Covers (e.g. soil) over the disposed waste provide good attenuation of radiation exposure and would be sufficient to control radiation exposures to well below acceptable levels. Attenuation to background levels can be achieved with suitable cover thickness.

5.3.2.4. Disposition of thorium stockpiles

As mentioned in a US Defense National Stockpile Center report on guidelines and procedures for thorium nitrate disposal,

> "The Defense National Stockpile Center (DNSC) proposes to end its stewardship of the thorium nitrate stockpile, currently stored at two U.S. locations, in a safe and environmentally sound manner, with minimum radiation exposure and risk to the workers, the public, and the environment. DNSC needs to perform the proposed action because the thorium nitrate stockpile is in excess to the needs of the U.S. Department of Defense. No other agency of the federal government has a need for this thorium nitrate, and there is no market for its sale."

TORTA II reflects the Brazilian experience in storing thorium compounds and salts and is characterized by ~30% moisture, 22% thorium, 5% REE and 0.9% uranium. Brazil also had developed the methodology for the recovery of thorium, uranium and REE from TORTA II. The current stockpile of 17 000 t TORTA II is stored in INB facilities at Caldas (13 000 t), Botuxim (3500 t) and Interlagos (500 t).

5.3.3. Mine waste management

Mine waste management techniques and procedures for the HMS industries and for monazite processing are to be considered under a carefully performed and reviewed waste management plan which details procedures for the waste generated from the operation of the mine and the land filling of production waste returned to the mine from the concentrator or plant. Waste management has to identify the streams and quantities of waste generated; detail waste management strategies for minimizing, reusing/recycling and disposing of waste; establish waste handling and collection protocols, including waste tracking procedures; formulate a waste monitoring programme; detail performance reporting and review requirements. It also has to follow the IAEA guidelines for radioactive waste management.

5.3.4. Mine closure

In the case of mine closure, the aim is to rehabilitate the mining and milling area to an acceptable post-mining land use based on a safe, stable and non-polluting environment. Mine closure and decommissioning of HMS operations are to follow the best practices and guidelines of the HMS industry, as well as the permanent reviewing of society demands for a sound and radiation free environment [84, 85].

6. SOCIOECONOMIC CONSIDERATIONS

Although the development of a mining project can provide important economic benefits to local and national economies, it can also result in unintended detrimental effects to both people and to natural resources. Since the social consequences of a mining project can have both positive and negative social impacts, it is now common to perform a social impact assessment to assist in managing change and thereby ensure a more sustainable and equitable environment.

The Equator Principles and the International Finance Corporation (IFC) Performance Standards provide a widely used risk management framework for the environmental and social assessment and management process. The 2012 edition of IFC's Sustainability Framework [100], which includes the Performance Standards, applies to all investment and advisory clients whose projects go through the IFC's initial credit review process after 1 January 2012. The IFC (2012) has established the following eight Performance Standards to help manage environmental and social risks:

- Performance Standard 1: Assessment and Management of Environmental and Social Risks and Impacts;
- Performance Standard 2: Labour and Working Conditions;
- Performance Standard 3: Resource Efficiency and Pollution Prevention;
- Performance Standard 4: Community Health, Safety and Security;
- Performance Standard 5: Land Acquisition and Involuntary Resettlement;
- Performance Standard 6: Biodiversity Conservation and Sustainable Management of Living Natural Resources;
- Performance Standard 7: Indigenous Peoples;
- Performance Standard 8: Cultural Heritage.

Each of the above issues requires careful consideration and must be addressed during the development of a new project. It is beyond the scope of this report to address these issues in detail; however, a few general comments are provided below.

6.1. POLICY AND REGULATORY GOVERNANCE

As noted earlier, it is possible, even likely, that in the future thorium will play an important role in energy security. If thorium is to be produced, its major source is the monazite phase contained in most HMS. In the case of HMS/monazite extraction in populated areas, a very stringent environmental impact study should be carried out as well as a proper NORM evaluation of the area before granting permission for exploration. Mining of HMS produces several ore concentrates, including monazite concentrate, which can be further processed to obtain REE and thorium. Until China's decision to reduce exports of REE concentrates, monazite was not utilized as a REE source and was typically diluted for final disposal into a pit or into the sea. Currently, interest in mining HMS for REE extraction has resumed and one of the outstanding questions is how to manage the extracted thorium until a commodity market for it arises. At present, in an ideal best practise situation, any radioactive products are stored, thereby observing both national and international radiation protection standards. Although the solution is known, it implies many management issues and associated logistics, regulated by policies, regulatory acts, governance and legal aspects set out by producing countries with respect to international standards, for example those issued by the IAEA. If thorium becomes a commodity market as a co- or by-product of REE production from monazite, then a better solution to the problem could become available due to increased research funding, although subject to the regulatory acts that will be in place for such a case.

6.2. ECONOMICS

The economic aspects of a project concerning monazite mining and processing have already been discussed. In addition, however, the economic implications in terms of royalties, tax revenue for local and national governments and local communities, as well as opportunities for employment and local and regional business development must also be taken into consideration but are not discussed in further detail here.

6.3. SOCIAL

The prospect of a mining project, processing facility and associated infrastructure commonly provides the promise (valid or otherwise) of economic benefits. However, the same project may also raise concerns and uncertainty in a segment of the community with respect to:

- Potential occupational health risks;
- Potential risks to the community;
- Potential for negative impacts to the biophysical environment;
- Potential effects on traditionally important activities such as hunting, fishing, trapping and medicinal plant harvesting.

In addition to the IFC 2012 [86] guidance for evaluating potential social impacts, there is often national and/or local guidance that must be considered. One example is the Mackenzie Valley Land and Water Board guidance for Community Consultation [87]. This engagement policy is designed to ensure that affected parties are able to:

- Develop an understanding of a proposed project or component of a project;
- Provide feedback during the engagement process on issues of concern with regard to a project;
- Work towards building relationships with proponents that are operating in an area.

The recent experience of Avalon/Thor Lake (see Case Studies: Canada) supports the importance of a comprehensive community engagement plan.

6.4. CONCERNS WITH RADIATION PROTECTION

REE resources invariably contain naturally occurring radioactivity at concentrations above general background levels. Public concerns about REE developments could in large part be addressed by development of an understanding of ambient radiation and by radiation dose assessments coupled with the application of proven and robust waste management strategies.

In addition to concern about workers' health, safety and potential radiation exposure, the presence of radioactive substances in the REE resource and subsequently in wastes, if not managed and communicated effectively, can become a public concern [86, 88]. This concern may be amplified by the following factors:

- Unfamiliarity with REE mining and processing by public and institutional stakeholders;
- Reported claims of harm at historical REE operations in other countries;
- Technical complexity of managing NORM radioactivity;
- Generation of three or four distinct waste types and deposition of these materials with diverse characteristics and levels of radioactivity in locations other than waste rock at the mine site such as process tailings, metallurgical residues and REE separation wastes;

- Detailed understanding of the distribution of radiological materials in all phases of the process and complete radiological exposure pathway assessments of all phases of the project by qualified independent third parties;
- A full discussion of the NORM content of the REE resource and natural background radioactivity with the public and institutional regulators;
- Public discussion of radiation doses to workers and the interested public from natural sources and from the proposed REE development;

  -A review, with public and regulators, of waste management options and the potential radiation dose and environmental impact from REE development during operations and following closure;

  -Selection of best options for development and waste disposal based on financial, environmental, regulatory and social considerations.

While the levels of radioactivity in most REE developments are low, and while technical expertise can ensure the design of safe operations and robust waste management strategies, the intuitive public response to the presence of NORM can derail any REE development. The recent experience in Canada (e.g. Matamec) illustrates the importance of gaining social acceptability in allowing a project to move ahead. Matamec, a junior mining exploration company had an agreement with a subsidiary of Toyota Motor Corporation to provide its REE output from its proposed Kipawa deposit in the Témiscamingue region of Quebec. There are reported cases of difficulties in social acceptance for uranium mining projects (BAPE 2015). Similarly, the Matamec REE project has elevated thorium levels, and a final outcome is yet to be determined.

6.5. UNFC-2009: E-AXIS CONSIDERATIONS

Nowadays, a questioning attitude towards extractive, processing and manufacturing industries is evident. Questions such as promoting wealth, creating jobs, responsible management, income sharing, value chain, etc., are at the focus. Thus, the E-, F- and G-axes of UNFC-2009 [89] capture this discussion:

> "The E-axis designates the degree of favourability of social and economic conditions in establishing the commercial viability of a project, including consideration of market prices and relevant legal, regulatory, environmental and contractual conditions;
>
> The F-axis designates the maturity of studies and commitments necessary to implement mining plans or development projects;
>
> The G-axis designates the level of confidence in geological knowledge and potential recoverability of the quantities."

With respect to the E-axis, public acceptance for developing the mining prospect is vital and this is where the so-called Social Licence to Operate is accounted for, whereby extraction economics is based on reasonable assumptions of social acceptance and on the quantities to be extracted locally or regionally. Social acceptance of the development of an extraction project refers to the local or regional community's and stakeholders' acceptance or the approval of an enterprise to be located and operated within a given predetermined area,

7. CASE STUDIES

7.1. AUSTRALIA

The Nolans Bore REE–P–U–Th–F deposit (Fig. 6) in the Northern Territory, Australia, consists of multiple veins and breccia zones filled with abundant fluorapatite, with associated REE and thorium mineralization [37].

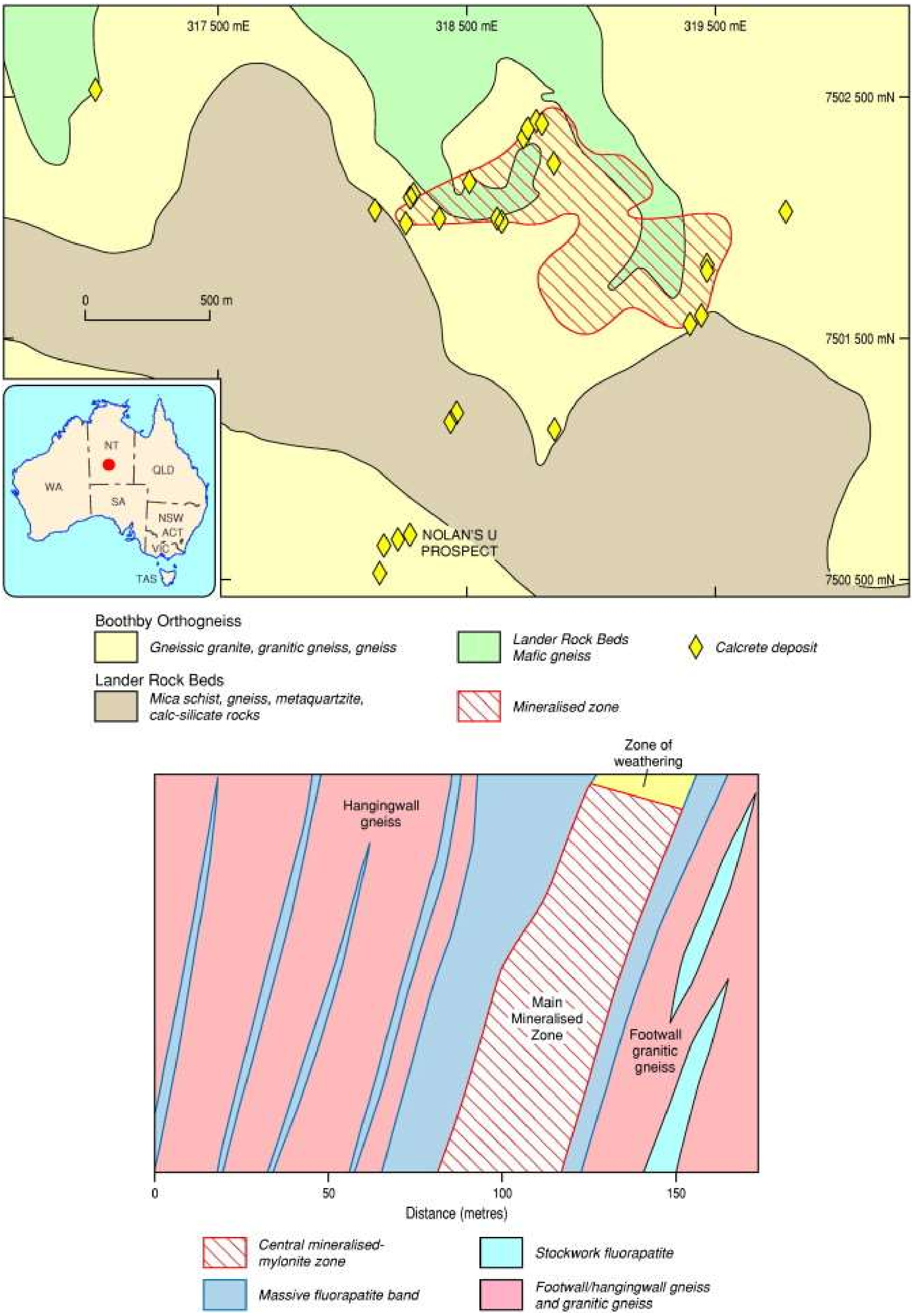

FIG. 6. Geological map and cross-section of Nolans Bore deposit (reproduced with permission of the Commonwealth of Australia (Geoscience Australia) 2018) [37].

These complex, multi-phase deposits are hosted by fault zones and are spatially, perhaps genetically, associated with nearby carbonatite/alkaline complexes and tin- and tantalum-rich pegmatites.Features of the vein and breccia deposits indicate several overprinting events of hydrothermal mineralization. The primary ore minerals are cheralite, thorite, allanite, bastnäsite, monazite, and several REE-bearing fluorcarbonates [37]. As of June 2012, Arafura Resources Limited reported total probable reserves in the Nolans Bore deposit, using a cut-off grade of 1.0% REO, totalling 24 Mt of ore containing 2.8% total REO, 12% P_2O_5 and 0.45 lb/t (0.2 kg/t) U_3O_8 [88]. An earlier estimate reported a Th content of 0.27% [37]. Veins of massive fluorapatite host most of the REE and thorium resources. When the REE concentrate is processed at Whyalla, South Australia, the thorium is separated as an iron–thorium precipitate and transported back to the mine site for long term storage as a possible future energy source.

7.2. BRAZIL

As early as 1886, monazite for Thorium was mined in Brazil from beaches in the Bahia region of Prado (Figure 7). This material was mostly exported to German and Austria amongst other European markets. It was used for Auer gas lamp net bags manufacturing. India and Brazil have vied for first ranking in thorium production from 1945. Prior to this India was the largest producer during the period 1915-1945 and Brazil up until 1915. As of 1955 the status of in situ identified monazite quantities in Brazilian resources is outlined in Table 12 [89].

TABLE 12. IN SITU IDENTIFIED MONAZITE RESOURCES IN BRAZIL, 1955 [89]

State	Monazite resource (1000 t)
Bahia	35–50
Rio Grande do Norte	50–100
Rio de Janeiro	100–150
Espírito Santo	200–300
Minas Gerais	50–130
Total	435–730

In order to process monazite, a chemical processing plant was built by ORQUIMA S.A., São Paulo by 1942 This was utilised for the manufacture of Rare Earth Elements, and became a major exporter of material to the United States of America. Until 1960, sands rich in monazite-rich were mined and processed at Buena beach, Rio de Janeiro in the SUPRA/SULBA plant. From this beneficiation, ~2000 t of mixed thorium chlorides (TORTA 2), were stockpiled in Minas Gerais region at INB's Caldas mine.

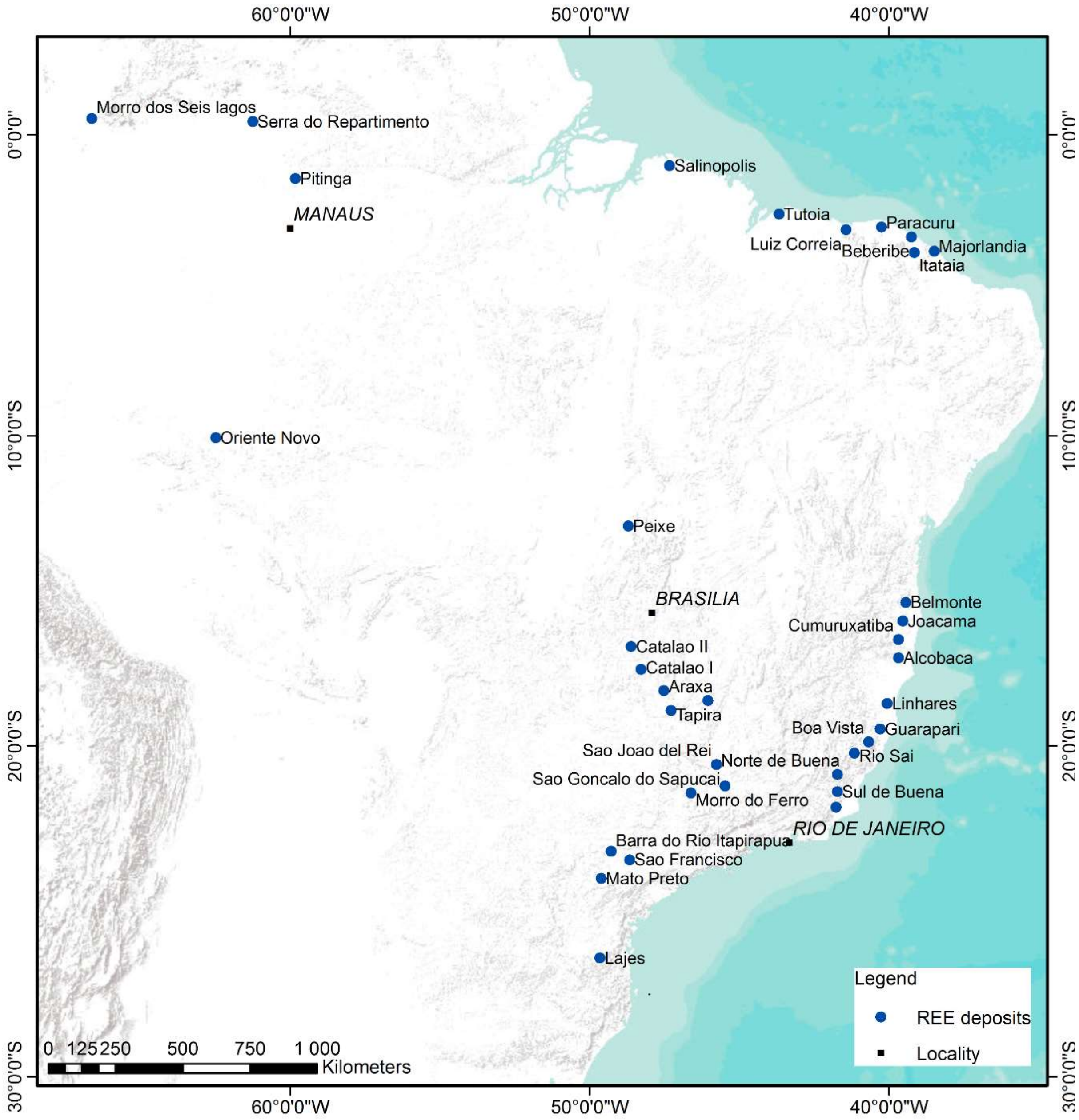

FIG. 7. REE deposits of Brazil. Adapted from [90].

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The Buena mine: Resources classification by UNFC-2009 [89]

The Buena mine, if viewed as an unutilized, but known, deposit, can be classified under UNFC-2009 as E2, F2.3, G1 and G2 (Table 13 [106]). This is appropriate if the deposit is routinely sampled for thorium content while producing REE and if the proposals for thorium reactor revival are to be taken into account. The deposit may be classified on this alternative basis as:

> E2: Extraction and sale is expected to become economically viable in the foreseeable future. Extraction and sale have not yet been confirmed to be economic but, on the basis of realistic assumptions of future market conditions, there are reasonable prospects for economic extraction and sale in the foreseeable future;

F2.3: There are no current plans to develop or to acquire additional data at the present-time owing to limited potential;

G1 + G2: Quantities associated with a known deposit that can be estimated with a high level of confidence (proven reserves) (G1) and with a moderate level of confidence (probable reserves) (G2).

Resource estimates at the lowest level of geological confidence are based on limited sampling and extrapolation. Except for the Buena mine, which has estimates at higher levels of confidence, these deposits are classed generally as 3, 3, 3, using the UNFC-2009 system of classification. the Buena mine is classified using UNFC-2009 as E1.1, F1.1, G1 and G2 as a monazite mine for REE (Table 13 [92]):

E1.1: Extraction and sale is economic on the basis of current market conditions and realistic assumptions of future market conditions;

F1.1: Extraction is currently taking place;

G1+G2: Quantities associated with a known deposit that can be estimated with a high level of confidence (proven reserves) (G1) and with moderate level of confidence (probable reserves) (G2).

TABLE 13. BUENA MINE, RIO DE JANEIRO, MONAZITE RESOURCES, [92]

Buena deposit	Resource (t)	Average grade (%)	Classification (CRIRSCO)	Categories (UNFC-2009)			Class (UNFC-2009)	Subclass (UNFC-2009)
				E	F	G		
Total monazite sands	608 690[a]	0.103 monazite	Proven + probable	1.2	1.1	1+2	Commercial project	In production (from earlier stockpiles)
ThO_2	31.35 based on 5% ThO_2 analysis of the total monazite		Proven + probable	3.2	2.3	1+2	Non-commercial project	Development unclarified (foreseen if Th reactors become a reality)

[a] Proven and probable resources of monazite and ThO_2 based on an estimated total of 1 292 282 t of in situ monazite sand resources at Buena, São Francisco de Itabapoana, Estado do Rio de Janeiro.

Mining at Buena (Figs 8 and 9 [93]) is carried out in a very basic approach:

- Organic-rich soil is stored for reclamation after removal;
- Removal of overburden;
- Extraction of monazite-rich ores through continuous removal;
- Ore transportation to the physical beneficiation plant;
- Production of concentrates and waste;
- Reclamation of the mined area is performed.

Physical beneficiation is conducted, together with site reclamation, is a two-step process of:

1) Heavy minerals fraction concentration of the monazite sands is undertaken by means of Humphrey's spirals, which generates an ilmenite, monazite, rutile and zircon concentrate. Palaeo-shoreline sand waste products are returned for reclamation operations;
2) Electromagnetic, electrostatic and gravimetric clean concentrate generation. The ore recovery for the heavy minerals is 85% overall.

Reclamation is undertaken concomitantly with the two-step concentration process whereby the waste materials are transported to fill mining trenches and the fills are covered with the stockpiled soil from the first step above.

The Buena orebody is a monazite beach placer sand. The mine recommenced operations using stockpiled ore in 2011 after being idle during a period of elevated Chinese production of REE. The Buena mine has been operating from stockpiled ores since 2011 (Table 14) but as of the time of writing is planning for closure [94, 95]. 10 000 t of zircon/rutile, 50 000 t of ilmenite and 7000 t of monazite was estimates [94] in remaining stockpiles. The operation is categorized therefor as E(1.2), F(1.1) and G(1 + 2).

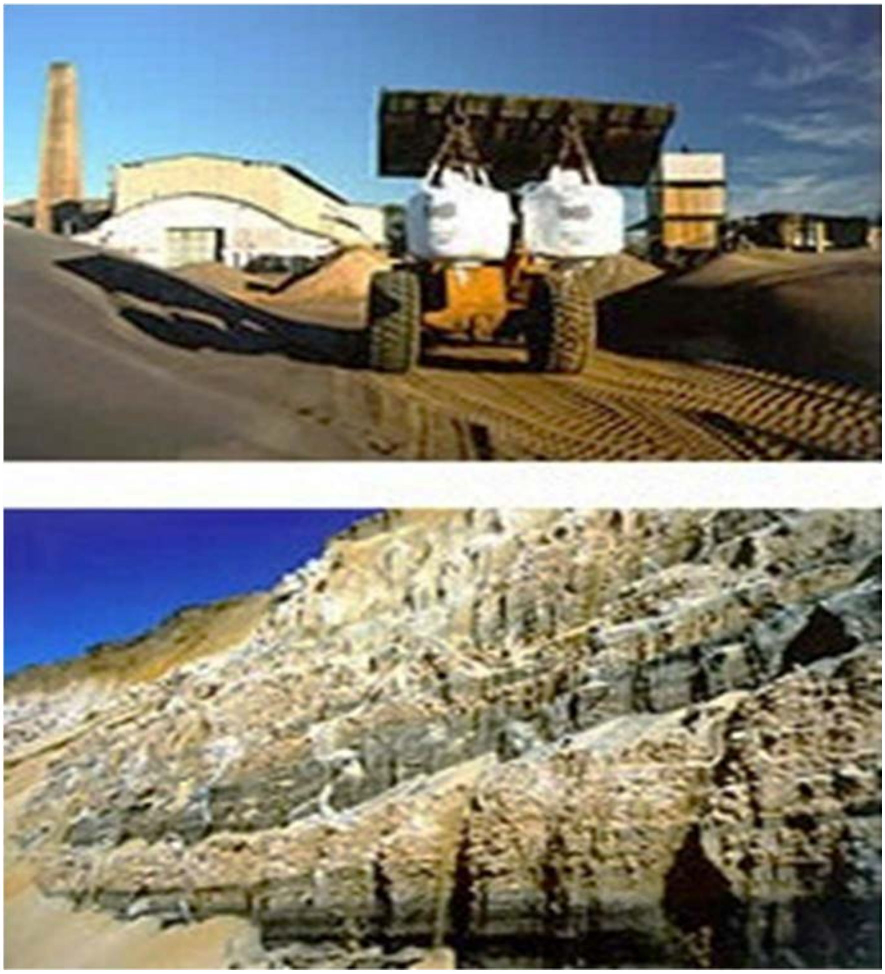

FIG. 8. INB's Buena mine, north-east of Rio de Janeiro (41°00′18" W, 21°24′36" S), is the only REE producing mine in Brazil (photograph by R. Villas-Boas).

VISTA EXTERNA DA UDES

VISTA INTERNA DA UDES

FIG. 9. Solvent extraction plant at the Buena mine in 1992–1993 (extracting REE). (photograph by R. Villas-Boas) [93].

TABLE 14. STOCKPILED ORES AT THE BUENA MINE IN 2011, 2012 AND 2013 (t)

Mineral (t)	2011	2012	2013
Monazite	1500	2700	600
Zircon/rutile	1450	1200	750
Ilmenite	10 500	12 000	10 500

7.3. CANADA

NORM is present at some level in resource-based industries, among them, uranium mining, phosphate fertilizer facilities, niobium and tantalum mining, as well as REE operations. While the main source of REE production is currently China, there are several emerging and potential REE developments in Canada and elsewhere. With minor exceptions, all REE deposits contain varied amounts of thorium- and uranium-based radioactivity.

7.3.1. General

In recent years, two major REE developments are the Thor Lake project, Northwest Territory and the Pele Mountain Project in Elliot Lake, Ontario.

Throughout the Canadian Shield, isotopes of uranium and thorium are naturally present at levels of ~3 and ~9 ppm, respectively. In some areas, they are more concentrated economically to mine, e.g. Elliot Lake, Agnew Lake and Bancroft in Ontario. Thorium is more concentrated at Agnew Lake (2 kg/t) than at Elliot Lake or Bancroft (0.5 kg/t) [96]. The Elliot Lake area was at one time the world's largest producer of uranium. As the ore grades and spot price for uranium decreased, the mines were gradually decommissioned.

Pele Mountain Resources is a Canadian resource exploration and development company focused on the REE and uranium project in Elliot Lake. Initially, the Pele Mountain project was based on the development of an underground mining operation (up to 9000 t/d), with recovery of both REE and uranium. Some 200 Mt of uranium tailings are secured in tailings management areas which contain recoverable quantities of REE. Pele Mountain Resources has considered the possibility of recovering REE from the tailings [97]. In such a case, some portion of the (roughly) 200 000 t of thorium present in the tailings could be recovered. In October 2014, Pele Mountain Resources announced a strategy to extract and separate REE from monazite concentrate imported from overseas at its Eco Ridge rare earth and uranium project.

Matamec Exploration Inc. has been evaluating the potential for development of the Kipawa REE–yttrium resource, which is ~65 km east of Temiscaminge, Quebec [98]. The resource contains concentrations of heavy REE. The Kipawa metallurgical process will be designed to isolate a REE concentrate from U and Th by a combination of ion exchange, solvent exchange and selective precipitation techniques. Both U- and Th-enriched precipitates are combined with the metallurgical residue for disposal. However, Th is potentially recoverable as the ore contains ~270 ppm Th. production of 10 000 t/d of ore at an average grade of 270 ppm Th is equivalent to a thorium output of ~2.7 t/d or 945 t/y. If 50% of the Th can be recovered, the site has the potential to produce ~500 t/y of thorium. As previously noted, the Matamec project is currently caught in a Quebec debate about mines associated with a uranium content, albeit very low at ~32 ppm.

7.3.2. Thor Lake

The Thor Lake project is a proposed REE mine with two infrastructure sites: the hydrometallurgical plant site and the Nechalacho mine and flotation plant site. Mineralization in the deposit includes light REE in allanite, monazite, bastnäsite and synchysite; yttrium, heavy REE, and tantalum in fergusonite; niobium in ferro-columbite; heavy REE and zirconium in zircon; and gallium in biotite, chlorite and feldspar in albitized rocks (Fig. 10) [99, 100].

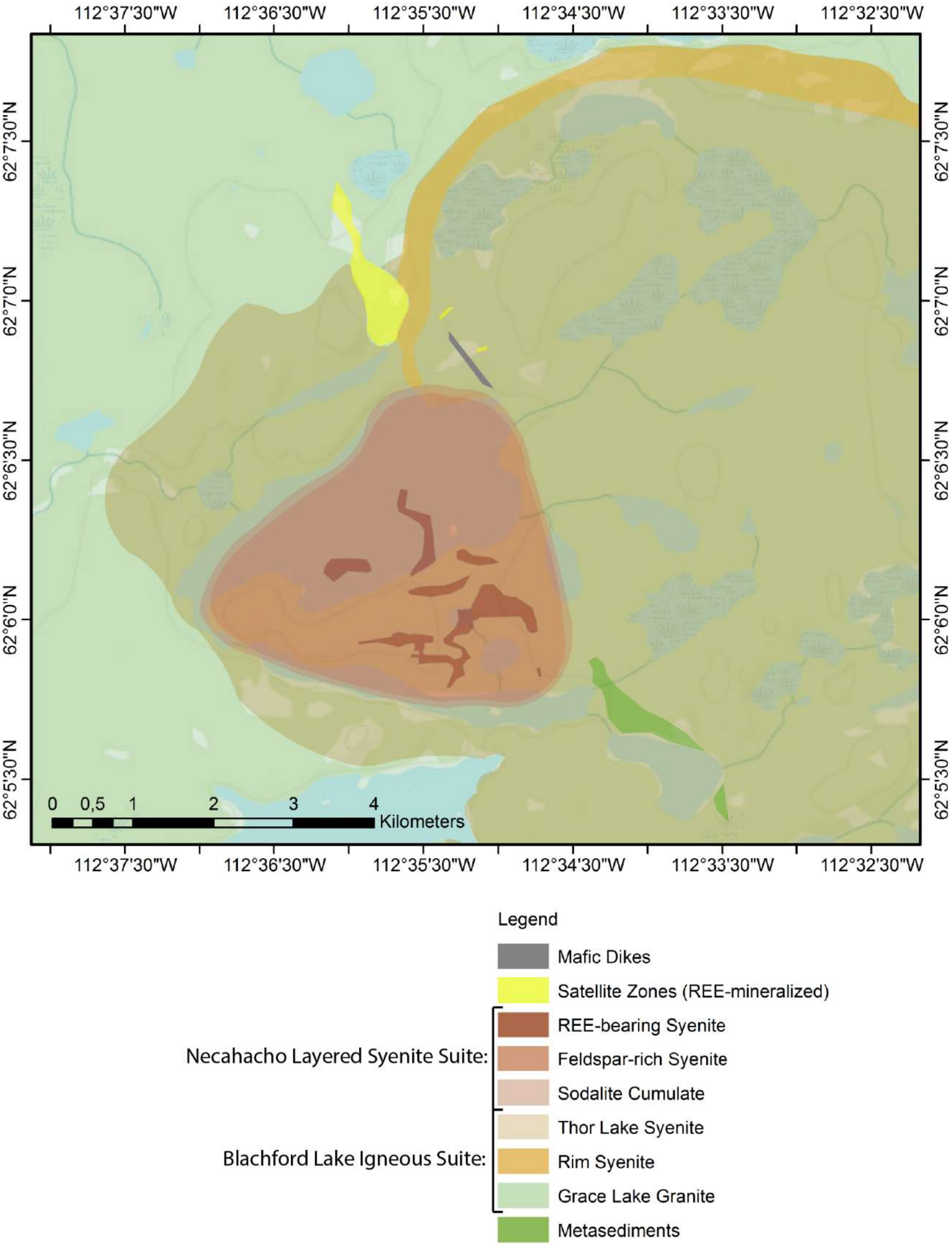

FIG. 10. Geological map of the Thor Lake area Adapted from [99].

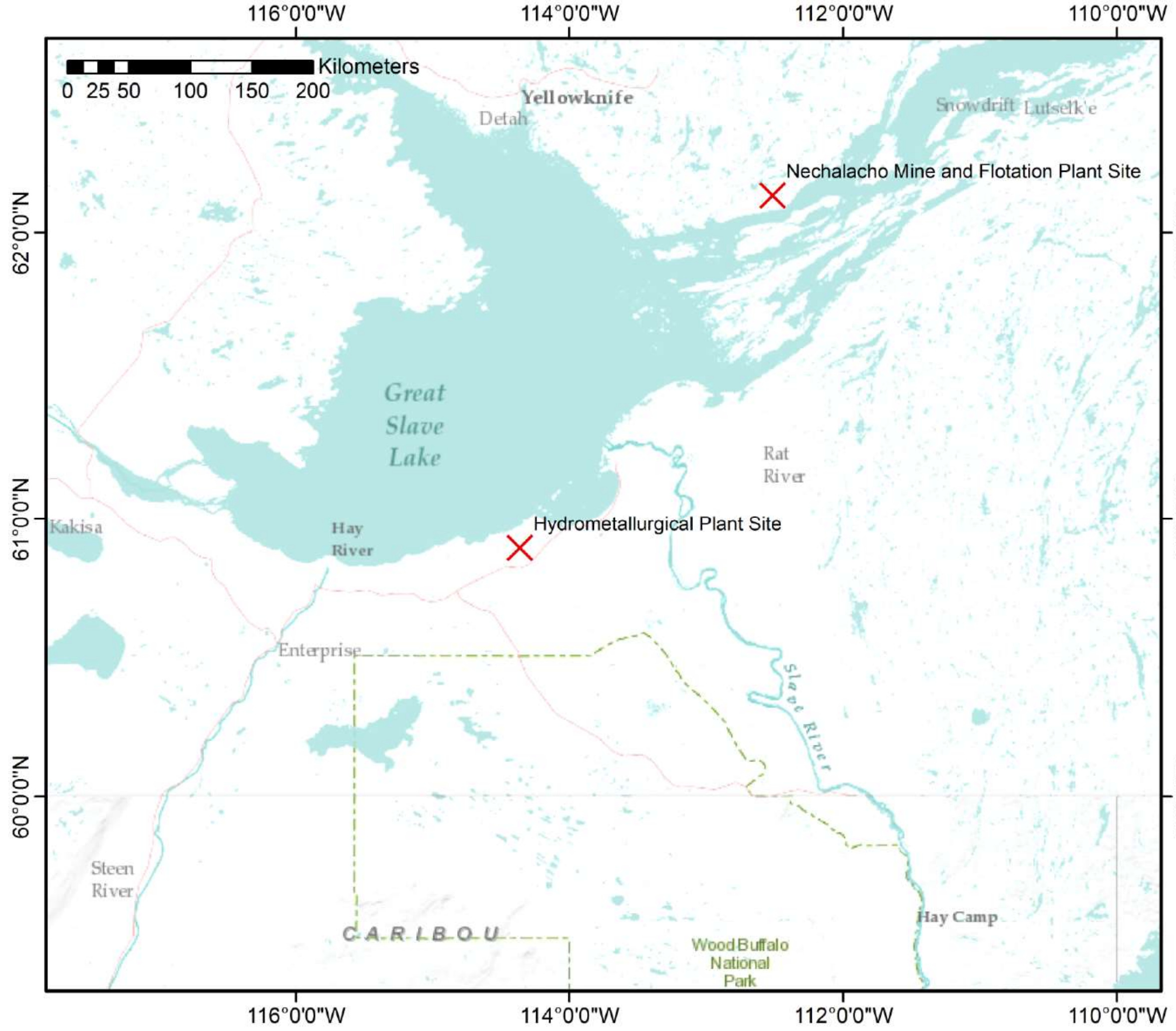

FIG. 11. Location of the Nechalacho mine and flotation and hydrometallurgical plants. Adapted from [101].

Avalon proposed mining and milling REO and carbonates, niobium, tantalum oxides and zirconium. The deposit has ~2% REO and would have been mined at 2000 t/d. An estimated 9 Mt of indicated resources were to be mined from the Nechalacho deposit alone. Construction of the mine and associated infrastructure would have required 2 years, followed by 18 years of active mining and 3 years to implement the closure plan. The Nechalacho deposit is located on Thor Lake, 5 km from the northern shore of the Hearne Channel of Great Slave Lake. The location has no road access and can only be reached by boat, helicopter, snowmobile or plane (Fig. 11).

The Thor Lake property comprises a total of six deposits, the largest of which, covering an area of 2 km^2, is the Nechalacho deposit [101]. The deposit is to be mined underground to an anticipated depth of 200 m using a long decline ramp to access the ore zone. An underground crushing circuit (primary and secondary) followed by screening is planned. Then the ore would be conveyed to the surface for further processing within the flotation plant (conventional grinding, crushing and flotation). A production of 360 t/d of ore concentrate is envisaged. The concentrate is to be shipped by barge to the hydrometallurgical plant site for further processing. The hydrometallurgical plant is to be situated at the former Pine Point Pb–Zn mine, ~165 km south-west of the Nechalacho mine and 11 km south of the southern shore of Great Slave Lake. The decommissioned Pine Point mine is now a brownfield site and is considered to offer the most environmentally and financially viable location for ore processing. After ore processing at the hydrometallurgical plant site, the product would be shipped by rail to southern markets.

In addition to REE and other metals such as niobium, zirconium and tantalum, the ore contains naturally occurring uranium and thorium at average concentrations of approximately 24 ppm and 130 ppm, respectively. Assuming a thorium content of 130 ppm and that an estimated resource of 9 Mt of ore could be mined from the Nechalacho deposit alone, then some portion of the 1200 t of thorium would potentially be available for by-product recovery if desired.

Since receiving its Type A Land Use Permit in April 2014 from the Mackenzie Valley Land and Water Board, Avalon also received its Type B Water Licence in May 2014. All necessary environmental management plans have been approved. These authorize Avalon to complete, in a phased approach, low impact activities, including site preparation, early camp erection, portal development and infrastructure upgrades (roads, power and water treatment). Technical review sessions related to the full construction and operations were held in Yellowknife with final hearings in 2015, followed up with further community engagement work, finalizing construction and operations, and environmental management plans. Engineering work for the mine and concentrator is complete.

The process design for the final hydrometallurgical plant is being updated. However, as of the end of July 2015, engineering work has been placed on temporary hold pending a final decision on the location of the hydrometallurgical plant. The original proposed site used in the feasibility study was Pine Point, but the new process design involves significant additional infrastructure requirements and the use of chemical reagents.

The Nechalacho rare earth elements project at Thor Lake received federal approval in 2013, but a downturn in commodities markets forced Avalon to put the project on the back-burner in 2014. At the time of writing (2019), construction of the Thor Lake Project has yet to start.

7.4. INDIA

A detailed description of Indian thorium deposits is given in Ref. [102].

7.4.1. Chavara deposit, Kerala

The Chavara deposit, extending from Neendakara in the south to Kayamkulam in the north, in Kollam district, Kerala, is characterized by leucoxene–ilmenite containing more than 60% TiO_2. It is being explored in three phases: (i) Barrier beach; (ii) Eastern Extension Phase-I and (iii) Eastern Extension Phase-II (Fig. 12).

The Barrier beach sector of the deposit extends over a coastal length of 22 km along a barrier beach with an average width of ~200 m between the Arabian Sea to the west and the TS canal to the east. The Eastern Extension Phase-I extends inland over a width of 1 km from the TS canal, whereas the Eastern Extension Phase-II extends further, over a width of 5–6 km. The deposit has been exploited for over 100 years for the production and export of ilmenite. Initially, the main producers were M/s Travancore Mineral Concerns, M/s Hopkins and Williams Ltd and M/s FXP Minerals Ltd.

In 1963, IREL became the successor of M/s Travancore Minerals Concerns and M/s Hopkins and Williams Ltd and acquired the assets of these companies. Kerala Minerals and Metals Ltd, a public sector company operating under the Government of Kerala, is the other producer.

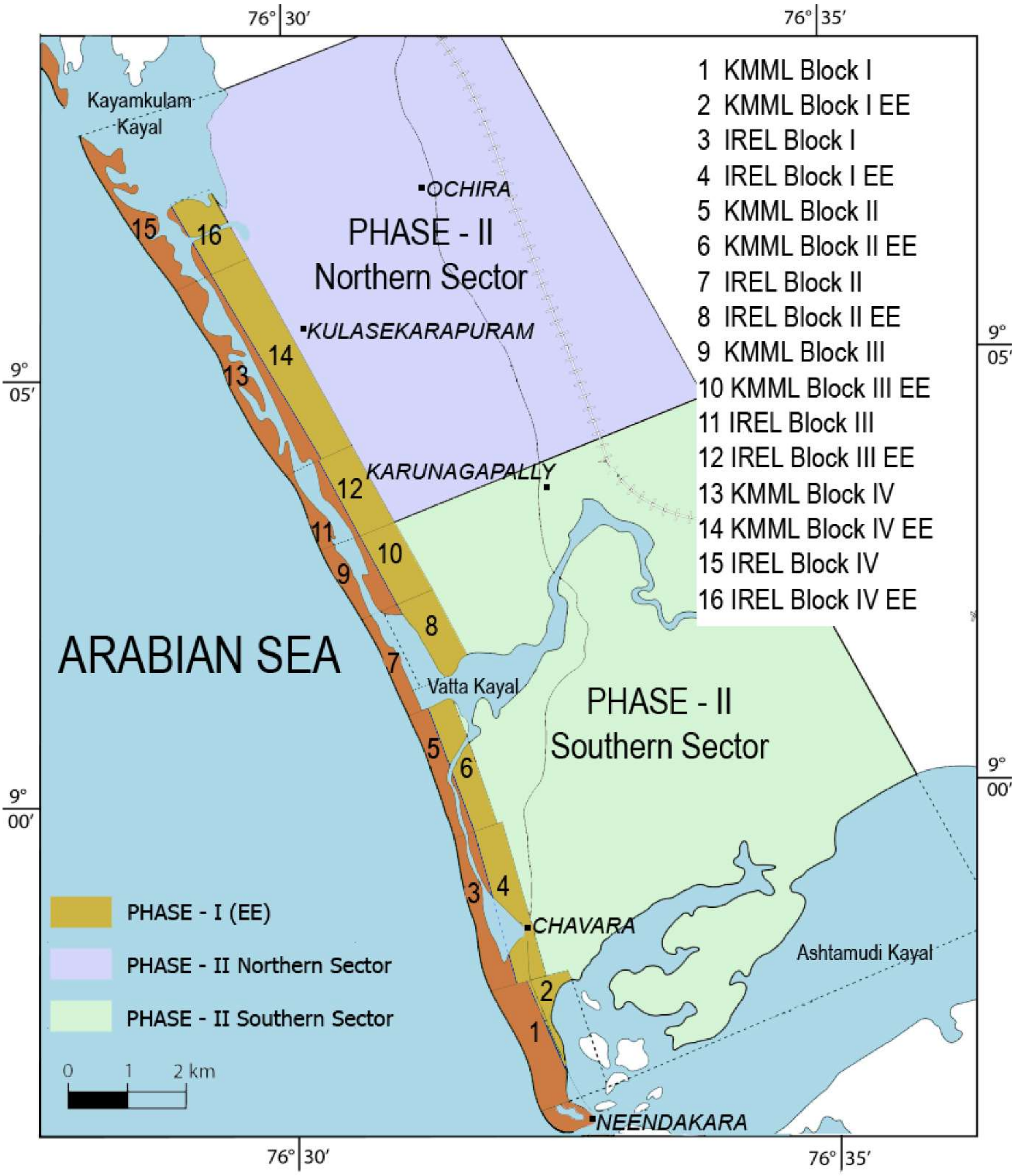

FIG. 12. The Chavara deposit, Kerala, south-west India. Adapted from [103].

7.4.2. Chatrapur deposit, Odisha

The Chatrapur heavy mineral deposit is located in Ganjam district, Odisha and extends over 18 km from Gopalpur in the south to Rushikulya river mouth in the north. It is currently being actively mined by IREL, a public sector company operating under the Department of Atomic Energy (Fig. 13).

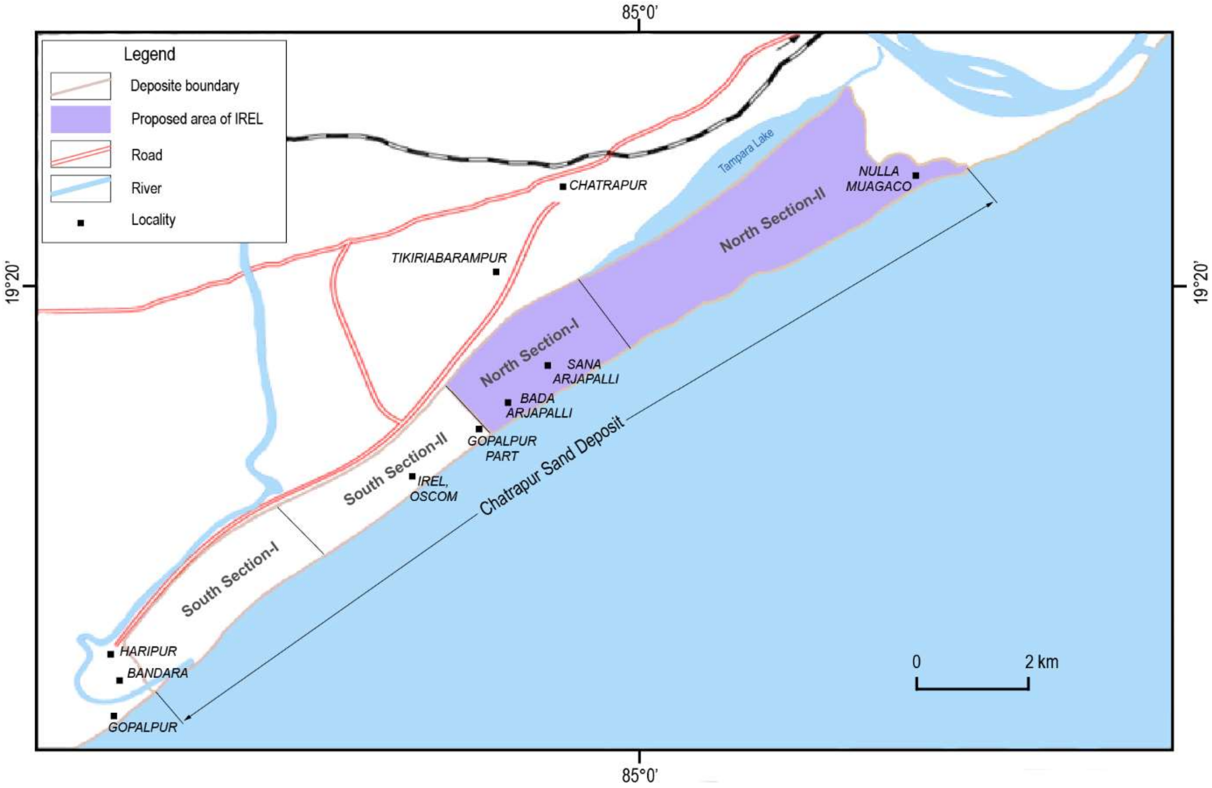

FIG. 13. The Chatrapur deposit, Odisha, south-east India (source: IREL).

The deposit extends over 18 km × 1.2 km and is divided into several sectors: South Sector-I (4.15 km), South Sector II (3.25 km), North Sector-I (2.66 km) and North Sector-II (7.97 km).

Initial investigations of the Chatrapur deposit date back to 1960–1962, during which time auger samples from dunes were drawn from a depth of ~2 m. The deposit was also explored in 1969–1972, where the sampling was carried out on a 30 m × 30 m grid and up to 2 m depth (labile zone), on a 30 m × 150 m grid in the stable zone (up to water table) by auger and 1.5 m below water table (average explored depth: 6.5 m), and on a 150 m × 750 m grid by Conrad bunka drilling. At a later period (1992–1994), detailed investigations (200 m × 100 m grid) were carried out in the southern sector. Currently, detailed sampling up to the full depth of the sand is being carried out.

7.4.3. UNFC-2009 classification

In India, the Indian Bureau of Mines, under the Ministry of Mines and thus part of the Government of India, maintains the National Inventory of Minerals (www.ibm.nic.in). Recently, the UNFC-2009 classification became widely accepted, although adapted to Indian requirements. To do so, all mineral deposits, irrespective of the mineral, are classified into seven categories, primarily based on the deposit configuration.

It is found that, contrary to their dimensions and continuity, the beach sand mineral deposits are grouped under the category 6: Placer and Residual Mineral Deposits of Hill and Valley Wash. However, the beach sand mineral deposits are observed to have distinct characteristics (Table 12), differing significantly from those of residual hill and valley wash deposits. Therefore, a new category for beach sand mineral deposits is under consideration, where a wider drilling interval is being proposed to define the G (geology) axis of the UNFC system.

Generally, the resources of beach sand mineral deposits, including that of monazite occurring in close association with ilmenite, rutile, leucoxene, zircon, garnet and sillimanite are categorized as G2 or G1 based on the above characteristics. Although the prices of the different minerals comprising the beach sand mineral assemblage fluctuates, there is overall economic viability of the industry, and hence, can be considered as either in the E1 or E2 category, along the economic axis. However, considering land use patterns (as some of the deposit areas are either inhabited or fall within cultivated land), the categorization on the economic axis may change on a case-to-case basis and from time-to-time. As the mineral processing flowsheets of beach sand minerals are well established, the deposits can be considered as F1 along the feasibility axis.

7.5. SOUTH AFRICA

In South Africa, several occurrences and deposits can be regarded as future or potential sources of thorium. The deposit at Steenkampskraal is chosen as an example. Other potential sources are added.

7.5.1. Steenkampskraal mine

The Steenkampskraal mine is the largest known monazite deposit in South Africa and is hosted by a charnockite–leucotonalite intrusion [12, 13]. It is located 70 km north of Vanrhysdorp, in Western Cape Province. The mine operated from 1952 to 1963, producing a monazite concentrate, sold mostly for its thorium content rather than for its REE content (Figs 14 and15). Following an extensive drilling campaign and feasibility study, Great Western Minerals Group Ltd announced that it will be a fully integrated REE producer and processor. However, in July 2015, Great Western became insolvent and its Steenkampskraal assets were acquired by Steenkampskraal Thorium Ltd (STL), a venture capital company that aimed to become a commercial producer of thorium-based MOX nuclear fuel in the next few years. A feasibility study quotes in situ resources of 559 000 t of ore with a ThO_2 grade of 2.14%, corresponding to a thorium resource of 10 282 t [104].

As a high grade, low tonnage monazite deposit, the Steenkampskraal mine may be classified as either a REE producer (with Th being stockpiled in a radiologically controlled area underground) or as a thorium producer with REE as co-product. On this basis, the deposit may be classified somewhat differently, if the UNFC-2009 codes are applied (see Table 15).

A nelsonite (magnetite–apatite–monazite) deposit hosted by a leucotonalite intrusion near Garies (in proximity to the Steenkampskraal deposit) may be mined for iron in the future. Metallurgical tests indicate that Th and REE can be easily partitioned into the slags and potentially stockpiled as a future commodity should STL become a thorium fuel producer. Currently, no data are available on the resource tonnage or the thorium grade of the deposit.

FIG. 14. *View looking west of the old workings at Steenkampskraal mine. Note the steep, 70° dip of the removed mineralized lode. (Photograph by M.A.G. Andreoli).*

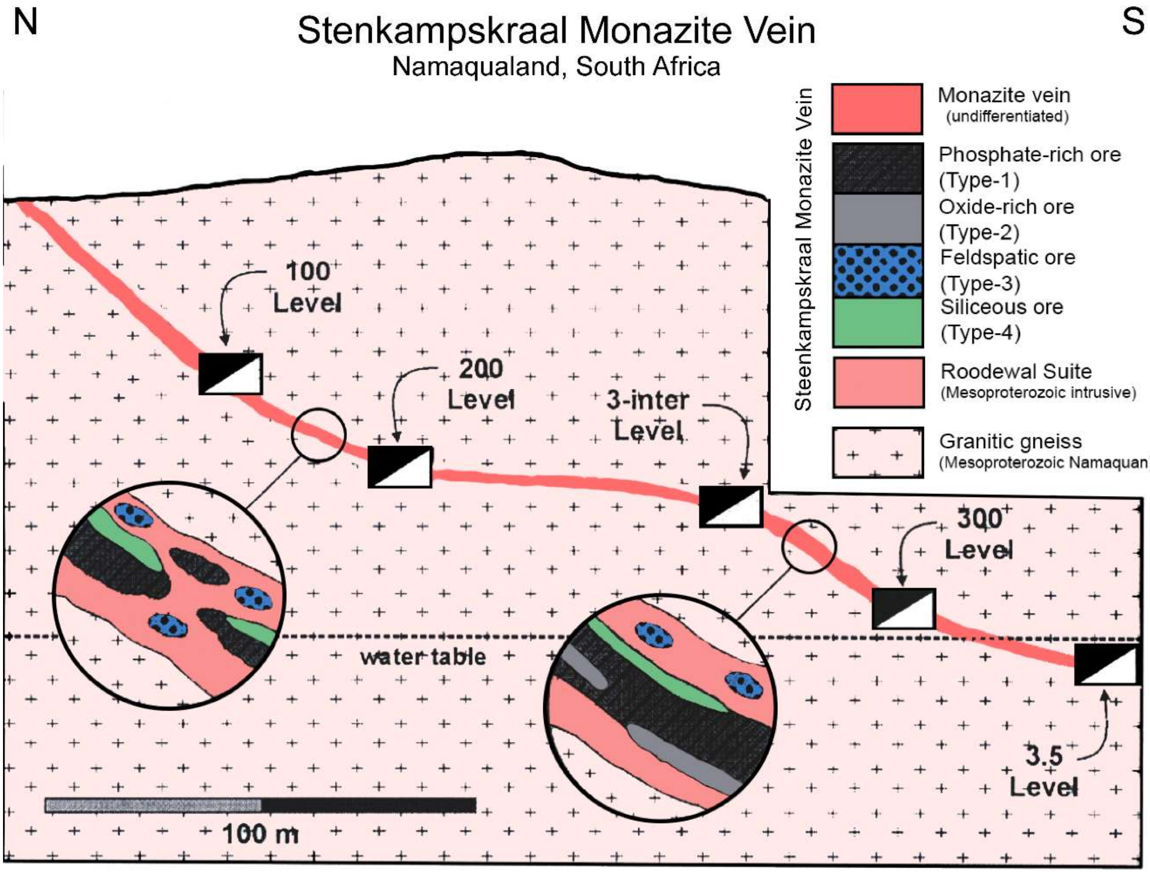

FIG. 15. *Section showing monazite vein, Steenkampskraal, South Africa (reproduced with permission of the European Journal of Mineralogy (www.schweizerbart.de/journals/ejm) [105], and Richards Bay Minerals).*

7.5.2. Richards Bay Minerals

Historically, Richards Bay Minerals (Fig. 16 [106]) produced concentrates of monazite (average ThO_2 grade of ~5% [107]) before 2003 from processing of HMS. Ticor and Namakwa Sands currently recover ilmenite, rutile and zircon. The ThO_2 content of the heavy mineral concentrates at Richards Bay is in the ~0.6–1 ppm range [108]. However, the large resources may be regarded as a potential future source of thorium.

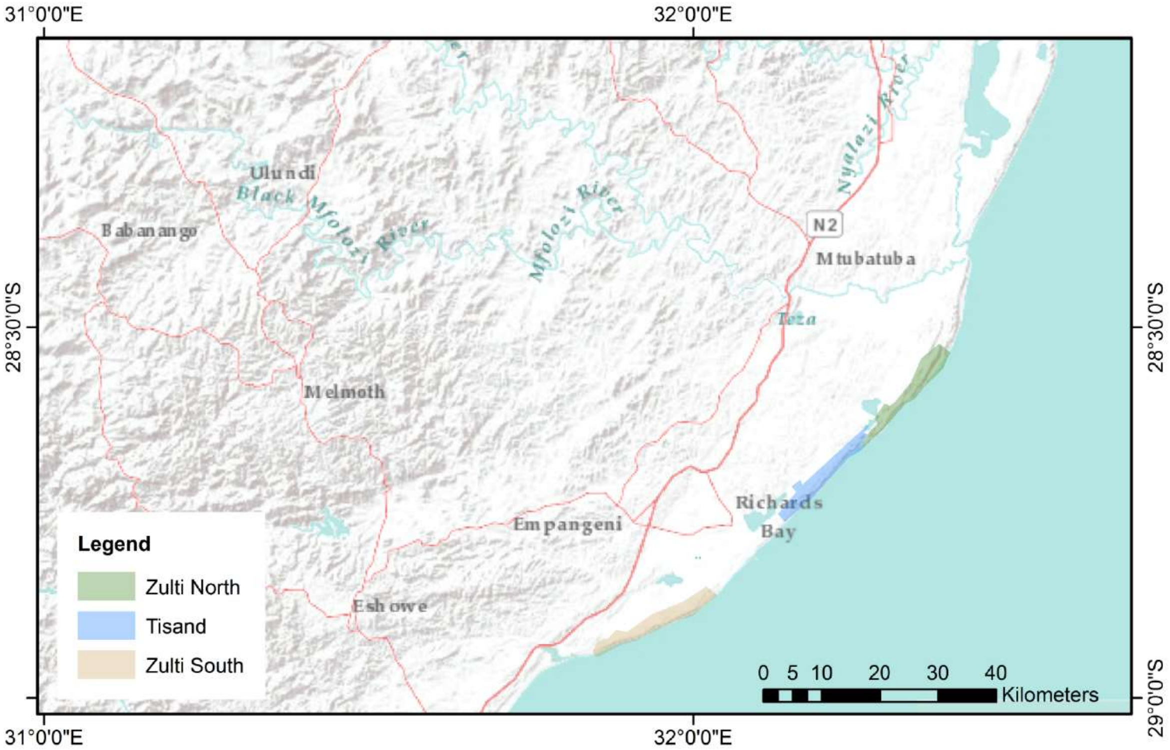

FIG. 16. Location map of Richards Bay Minerals' operations. Adapted from [106].

Among the numerous carbonatites and alkaline igneous complexes scattered across South Africa, only the Phalaborwa complex may be considered a potential source of thorium. The deposit was first mined open cast, but is now an underground operation, exploited for copper, with magnetite, zircon, vermiculite and other commodities as by-products. Historically, uranothorianite (ThO_2 ~2.3%, U_3O_8 ~25.7%) was recovered and calcined for the recovery of uranium with thorium being disposed at a the site under radiological control [109].

7.5.3. Zandkops Drift

The Zandkops Drift monazite–crandalite-bearing intrusion in the Namaqualand coastal belt is located 26 km south-west of Garies. This pipe-like body has been extensively drilled in recent years by Frontier Rare Earths as a low grade, high volume source of REE. However, company data indicate that the content of the ore is 178 ppm Th [109]. It seems unlikely that thorium will be produced from the deposit.

7.5.4. UNFC-2009 classification of South African deposits

Classification of selected South African deposits, according to the UNFC-2009 scheme, is presented in Table 15.

TABLE 15. SOUTH AFRICAN REE AND THORIUM RESOURCES CLASSIFIED ACCORDING TO UNFC-2009

Deposit/commodity	Quantities (t)	Average grade (%)	CRIRSCO classification	UNFC-2009 categories			UNFC-2009 class	UNFC-2009 subclass
				E	F	G		
Steenkampskraal								
Total REE + Y+ oxides	605 000 (includes 60 000 inferred)	14.4 (as oxide)	Proven + probable reserves	1.1	1.3	1+2+3	Commercial project	Justified for development
Thorium	559 000 (includes 60 000 inferred)	2.14	Proven + probable reserves	2	1.3	1+2+3	Commercial project	Justified for development
HMS								
Ilmenite + rutile + zircon	Very large, unspecified	Not available	Proven + probable reserves	1.1	1.3	1+2+3	Commercial project	In production (Ticor)
Monazite	Not available		Probable	3	2	3	Non-commercial project	Development unclarified (Namakwa Sands)
Phalaborwa								
Polymetallic	Very large, unspecified	Not available	Proven + probable reserves	1.1	1.3	1+2+3	Commercial project	In production
Thorium	Not available		Probable	3	2	3	Non-commercial project	Development unclarified

7.6. USA

7.6.1. Mountain Pass REE deposit, California

This case study involves a UNFC-2009 classification of a REE–thorium deposit in California. The deposit is classified both as a source of REE and as a potential source of thorium. The deposit considered here is the REE orebody, which is hosted within a massive Sulphide Queen carbonatite [18, 110]. It is the largest known REE deposit in the USA and is exploited by the Mountain Pass mine. The mine and on-site mineral processing plants, which exploit this deposit, are owned and operated by Molycorp Inc. [27] (Figs 17 and 18) [17, 111]. After an eight-year hiatus, Molycorp resumed mining operations in late 2010 and continued until August 2015, when Molycorp announced that the operation would be put on care and maintenance. The Mountain Pass mine came into production by the mid-1960s. Until 1985, when China started production at a large scale, this dominated global supply. China completely dominated the REE market by 2002. Low levels of geological exploration resulted from limited demand for Th resulted. Owing to recent interest in research for Th-based nuclear reactors, new evaluation of resources of thorium bearing deposits may be needed. Reference should be made to the IAEA's ThDEPO database for thorium-bearing deposits.

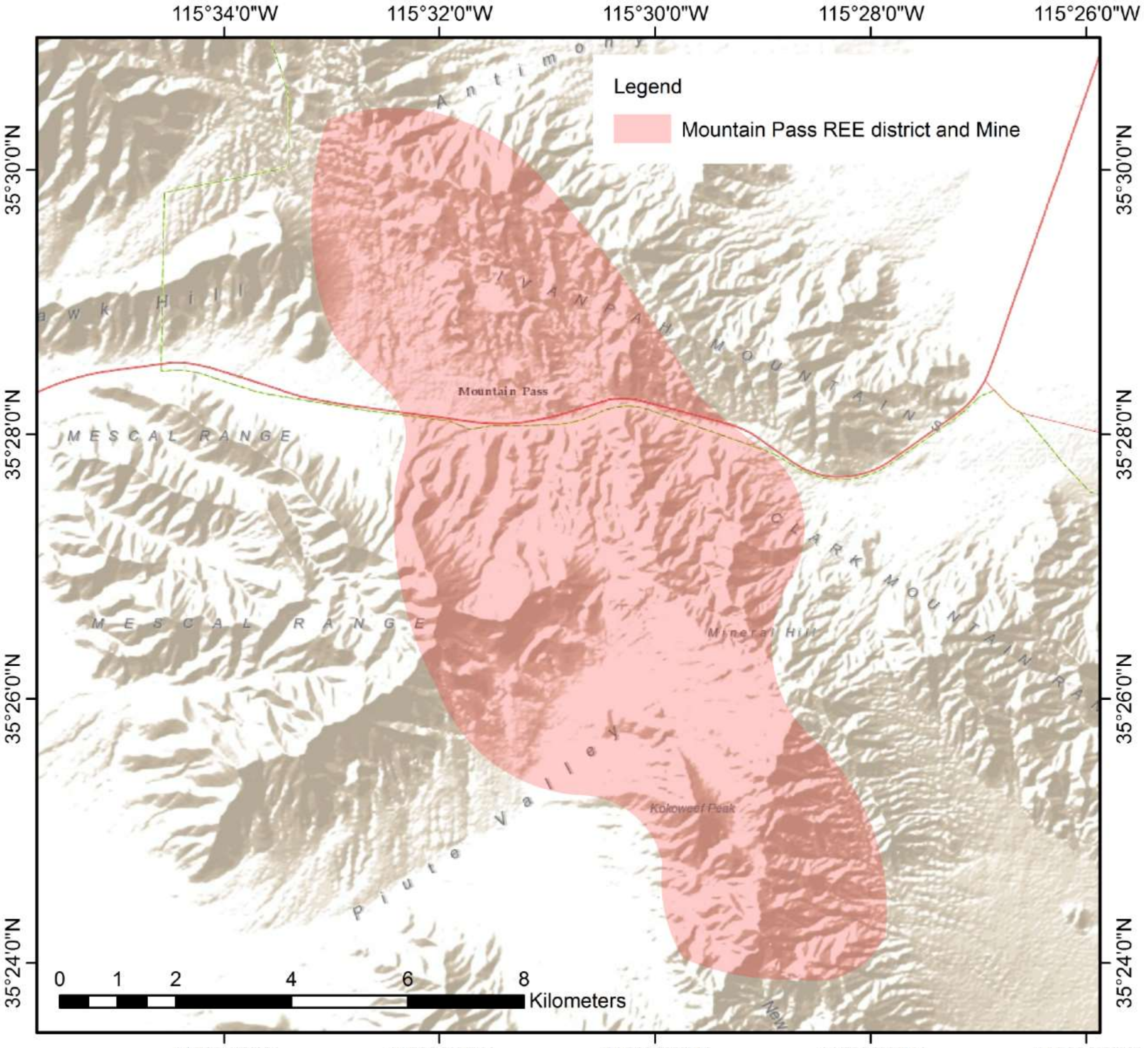

FIG. 17. Location map of Mountain Pass REE district and mine (reproduced with permission of the US Geological Survey and adapted from [17, 111].

The REE orebody is a potential source of thorium either as a by-product or co-product of REE production. The thorium content is chiefly due to monazite, which is closely intergrown with REE minerals and is thus extracted during the mining process. Monazite concentrations vary from trace amounts to locally abundant [18].

FIG. 18. The Mountain Pass mine of Molycorp Inc., in south-east California. In 2015, it was the only active REE mine in the USA. The orebody, which is thought to be the largest REE resource in the USA, is a carbonatite intrusion. (Photograph by B. Van Gosen, US Geological Survey).

According to Molycorp, the Sulphide Queen carbonatite (i.e. the Mountain Pass orebody) has proven and probable reserves of 16.7 Mt of ore with average grade of 7.98% REO, based on a cut-off grade of 5% REO [27]. The US Geological Survey recently conducted reconnaissance bulk sampling of ore exposed in the open-pit mine (~1 t of composited ore was collected). Within the high grade REE ore, an average thorium content of ~0.025% was reported. This is almost the same as the average thorium content obtained by previous geochemical studies of this carbonatite [48]. These data imply that, on average, ~0.25 kg of thorium will be obtained for every tonne of ore mined from the deposit. However, because the data were obtained by limited sampling, the average thorium content of ~0.025% obtained by previous work is biased. This could mean that, as mining advances, monazite concentrations will be found to differ significantly across the carbonatite orebody. For the purpose of discussion, an orebody estimated to comprise more than 16.7 Mt of carbonatite with an average thorium content of ~0.025% would host an estimated thorium resource of >4200 t. As the estimates are based on limited exploration and sampling, they must be regarded at the lowest level of geological confidence.

The mining and processing operations were devoted only to the recovery and separation of REE. The company did not report plans to recover thorium in the near future. In 2015, the last year of production from the Sulphide Queen carbonatite, after REE separation the thorium-bearing and other residues were stored in the tailing's impoundment. Therefore, to recover the thorium in the future, the process flowsheet and/or further reprocessing of the tailings would need adaptation.

7.6.2. Classification of the Mountain Pass mine by UNFC-2009

With regard to the operations to mine and produce REE, the Mountain Pass mine would be classified as E1.1, F1.1, G1 and G2 according to UNFC-2009. That is, based on the REE operation, it is classified into the following categories and subcategories (Table 16):

E1.1: Extraction and sale is economic on the basis of current market conditions and realistic assumptions of future market conditions;

F1.1: Extraction is currently taking place;

G1, G2: Quantities associated with a known deposit that can be estimated with a high level of confidence (proven reserves) and with a moderate level of confidence (probable reserves).

On the other hand, as a known, unutilized thorium deposit sampled for thorium content at a reconnaissance level, the Mountain Pass mineral deposit may be classified as E3.3, F2.3 and G3 according to UNFC-2009:

E3.3: On the basis of realistic assumptions of future market conditions, it is currently considered that there are no reasonable prospects for economic extraction and sale in the foreseeable future;

F2.3: There are no current plans to develop or to acquire additional data at the time owing to limited potential;

G3: Quantities of thorium associated with a known deposit that can be estimated with a low level of confidence.

TABLE 16. MOUNTAIN PASS REE AND THORIUM RESOURCES CLASSIFIED ACCORDING TO UNFC-2009

Commodity	Quantities (t)	Average grade (%)	CRIRSCO classification	UNFC-2009 categories			UNFC-2009 class	UNFC-2009 subclass
				E	F	G		
Total REO	1 333 000[a]	7.98 (as oxide)	Proven + probable reserves	1.1	1.1	1.2	Commercial project	In production
Thorium	4200	0.025 (elemental weight)	Inventory[b]	3.3	2.3	3	Non-commercial project	Development not viable

[a] Proven and probable REE reserves based on an estimated 16.7 Mt of carbonatite ore (grades and tonnages for the categories of REE reserves are combined in the public report).

[b] Not defined in CRIRSCO template.

8. CONCLUSIONS

This report presents the possibilities for the production of thorium as a co/by-product from REE-bearing minerals. There is a significant potential to produce thorium compounds during the production of REE. Thorium often also occurs in nature associated with uranium. However, under specific circumstances, thorium may form deposits that do not contain uranium (or only in very small amounts) and is associated with other elements. Deposits of major importance, where thorium can be available as a by-product of REE and rare metal production, are found in specific geological environments.

Thorium deposits can be classified into:

- Carbonatites;
- Alkaline/peralkaline rocks;
- Vein-type;
- Metamorphic type;
- Placers.

Carbonatites

The majority of carbonatites comprise 50% or more primary carbonate minerals (dolomite, calcite and/or ankerite). A characteristic of carbonatites is their enrichment in volatiles (CO_2) and in HDSE, especially REE with associated enrichments in Th. Examples occur in Australia, Brazil, Canada, the Russian Federation, Scandinavia, South Africa and the USA.

Alkaline/peralkaline rocks

Alkaline and peralkaline rock types containing thorium resources are typified by higher contents of alkali elements (Na and K) than Al (i.e. $Na_2O + K_2O > Al_2O_3$). HFSE, especially REE, Y, Nb, Ta, Zr, U and Th, are frequently enriched in these rocks with concentrations locally reaching economic grades. Deposits occur in alkaline plutons, magmatic layered complexes, and associated veins and/or dykes. Examples are mainly polymetallic, such as the Thor Lake deposit in Canada or the Kvanefjeld deposit in Greenland.

Vein-type

Vein-type mineralization is described as discordant mineralization mostly inclined in various country rocks occupying faults, joints or fissures. Vein-type deposits, including dykes, often show a genetic relationship to magmatic intrusions (granites, alkaline rocks, carbonatites). They can be monometallic or polymetallic, with concentrations of base metals, rare metals, uranium, thorium and REE. Examples include the Lemhi Pass deposit in the USA (uranothorianite) and the Steenkampskraal deposit in South Africa (monazite vein), Nolans Bore in Australia (rich in REE, fluorapatite, uranium and thorium). At Steenkampskraal mine in South Africa, the monazite–apatite veins are associated with charnockites and leucotonalites.

Metamorphic type

This type consists of thorium concentrations in metamorphosed or metasomatized rocks. Thorium-bearing minerals are mostly in finely dispersed form, on joints, schistosity planes, etc. Host rocks of this type can be anatexites, migmatites, pyroxenites, gneisses and schists, as well as contact metamorphic rocks such as skarn, hornfels and marbles. Examples include deposits in southern Kerala in India and the Mary Kathleen deposit in Australia.

Placer deposits

Resistant sand-sized grains of hard, high specific gravity minerals accumulate along with sand, silt and clay in coastal, stream and river environments, locally forming economic concentrations of HMS. Monazite is the dominant REE- and Th-bearing mineral in HMS, from which such elements may be recovered. The ages of placer-type deposits vary from Archaean (e.g. the palaeo-quartz-pebble conglomerates in the Witwatersrand Basin in South Africa) to Tertiary. Recent aged HMS deposits (black sands) exist chiefly in coastal areas in Australia, Brazil, India, Mozambique, South Africa and the USA.

Global thorium resources were estimated in 2013 at 6.2 Mt, although uncertainties in resources exist in several countries, and thus the world total may be more than 7 Mt Th.Total resources of thorium in placer-type deposits are estimated worldwide to be ~2.2 Mt, which represents 35% of total thorium resources. Carbonatite-hosted deposits are estimated to amount 1.8 Mt of Th, which represents 29% of the total resources. Typically, the carbonatite-hosted deposits are enriched in REE and/or Nb/Ta. Vein-type deposits are estimated to amount to 1.5 Mt of Th, representing 25% of the total resources. Alkaline and peralkaline rock-type deposits contain 6 Mt of Th, representing 9% of the total resources.

Currently, recovery of thorium as a by-product of REE production from monazite is the most likely option. Current world production of REE is estimated at around 110 000 t/y. Thorium concentration in the monazite varies depending on the deposit, and thus the quantities of thorium that might be available through separate recovery is unknown. India is currently the sole country where thorium is extracted from monazite obtained by separation from other heavy minerals in placer deposits.

Global (Brazil, India, Malaysia, Vietnam) monazite production in 2013 had a theoretical Th content of around 400t Th at an average grade of 6% Th. The recovery of thorium from monazite is possibly the most realistic option in the near term. However, if demand for thorium were to occur, other sources of recovery of by-product thorium may become available.

In conclusion, thorium resources as co- and by-products of uranium, REE, rare metals and base metals are significant, and given a renewed interest in the use of thorium as a possible nuclear fuel, then these resources could be important in the future.

Careful considerations of the mineralogy will open up possibilities for co/by-product recovery of thorium. Thorium is an important energy source and could be used as a fuel in various nuclear power designs. However, due to the challenges in processing thorium compounds, the need for initial fissile material stock such as enriched uranium or plutonium, and the relatively easier availability of uranium, thorium is not currently widely used as a nuclear fuel. Countries like India and China have ambitious thorium utilization programmes. As technology improves, it is expected that some of the challenges in using thorium will be overcome and its use may become widespread. Therefore, it will be of economic prudence not to lose thorium to the waste stream when processing thorium-bearing minerals. Apart from creating a radiological waste problem, it is also wasting valuable material that has a dense energy value. As the world faces an unprecedented climate crisis, the role of low-carbon fuel sources such as thorium will gain importance. A more pragmatic approach will be to store thorium safely so that the stockpiles will be available as a source of sustainable, low-carbon energy for the future.

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GLOSSARY

allanite. Ca- and REE-bearing silicate

anorthosite. Rock essentially containing Ca-feldspar, minor pyroxene ± olivine

auger drilling. Device for drilling holes to recover unconsolidated material

bastnäsite. $Ce(F,CO_3)$

carbonatite. Rock with more than 50% magmatic carbonate minerals (calcite, dolomite, ankerite, etc.)

charnockite. Rock with K- and Ca-feldspar, orthopyroxene, quartz

coltan. Complex oxide approximating to $(Fe,Mn)(Nb,Ta,Sb)_2O_6$. The dominant niobium mineral in coltan is columbite, and the dominant tantalum mineral is tantalite

conrad bunks. Device to collect unconsolidated material, used in mining for heavy minerals in placers

crandalite. Ca-Al-phosphate with a OH-group

enderbite. Charnockite with magnetite

eudialyte. Complex Zr-silicate with ~7% REO

fergusonite. $(YNbO_4)$

fluorapatite. Ca-phosphate enriched in fluorine

khondalite. Metamorphic rock with quartz, manganese, garnet

leucotonalite. Quartz diorite, magmatic rock, enriched in quartz and Na-plagioclase

leucoxene. Altered ilmenite

monazite. Ca-phosphate with thorium $(Ce,La,Nd,Th)(PO_4)$

peralkaline rock. Magmatic rocks deficient in Al, characterized by $(K + Na) > Al$

PUREX. Plutonium recovery by extraction

pyrochlore. Complex oxide containing Ti, Nb, Ta, rarely Th

Red Book. Joint publication of the OECD Nuclear Energy Agency and the IAEA

spallation. Break-up of a bombarded nucleus into several parts

thorite. $(Th,U)SiO_4$

THOREX. Thorium recovery by extraction

tonalite. See leucotonalite, less excess quartz

ABBREVIATIONS

BSM:	Beach Sand Mineral
GW(e):	Gigawatt electric
HFSE:	High Field Strength Elements
HMS:	Heavy Mineral Sands, beach sands containing economically attractive mineral components, also known as placers or black sands
LEU:	Low Enriched Uranium
MW·d/t:	Megawatt-days per tonne
NORM:	Naturally Occurring Radioactive Material
QPC:	Quartz Pebble Conglomerate
RAR:	Reasonably Assured Resources
REE:	Rare Earth Elements (see also REO)
REO:	Rare Earth Oxides. Elements in the Lanthanide Group of the Periodic Table: La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu
THM:	Total Heavy Minerals
UNFC:	United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (for uranium and thorium)

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Thiruvanantapuram, India: 17–21 October 2011

Vienna, Austria: 2–6 July 2012

Vienna, Austria: 23–27 September 2013

Technical Meeting

Thiruvanantapuram, India: 17–21 October 2011

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International Atomic Energy Agency
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ISBN 978–92–0–163319–4
ISSN 1011–4289